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THESIS

A GENERALIZED APPROACH TO
AIR DEFENSE COMBAT MODELLING

by

Cho, Chung Koo

Lee, Yong Il

September 1985

Thesis Advisor:

Jack B. Gafford

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A Generalized Approach to Air Defense Combat Modeling

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
September 1985

ABSTRACT

This thesis presents a critique of air defense submodels in VECTOR-2 and CORDIVEM. The critique is used to develop an improved approach to modeling air defense against overflights. The proposed model design makes extensive use of pre-processing subprograms in order to increase model resolution. It also offers the analyst a framework for constructing particular models to satisfy specific objectives.

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I. INTRODUCTION

A. BACKGROUND

In modern warfare, air defense against high performance aircraft is vital. In general, air defense is a highly variable process. Unpredictable factors such as weather, terrain, aircraft performance, tactics, system performance, and operator performance greatly affect the outcome. Air defense modeling, in large-scale combat models, has encountered problems dealing with this high variability. The current modeling has concentrated on analyzing air defense effectiveness by aggregating many factors. Two large combat models, CORDIVEM and VECTOR-2, have used aggregate air defense models in an attempt to evaluate the effect of air defense on overflight aircraft. The designers have tried to represent warfare in a realistic, accurate manner. However, they have ignored factors such as command and control, terrain, and enemy electronic warfare (EW) capabilities. Accounting for these factors usually requires an increase in model resolution which has been considered unacceptable.

Command and control issues have been resolved by assuming that firing units act autonomously. Terrain effects have been ignored because most terrain models require many computations and large data bases. EW capabilities have been disregarded because their effects on air defense radars are involved and require extremely high resolution modeling to yield reliable results. In general, the air defense models used in corps/division level studies have sacrificed detail for computational simplicity.

B. THE PROBLEM

When an air defense model disregards the factors of command and control, terrain, and EW, the predictions concerning enemy aircraft attrition rates can be seriously overestimated.

For example, today's high performance aircraft are capable of flying low altitude, long range approaches which make maximum use of terrain masking. Such tactics greatly decrease the aircraft's vulnerability to ground air defense and enhance survivability. Moreover, it may be possible for some aircraft to completely avoid radar detection. Current aggregate air defense models encounter difficulty analyzing such situations. Developing models which consider command and control, terrain, and EW effects obviously requires more resolution and model complexity.

Can improvements be made which address the above shortcomings without making these large-scale models overly cumbersome and unresponsive ?

C. THESIS OBJECTIVES

The objectives of this thesis are to :

1. Analyze the air defense overflight models used in CORDIVEM and VECTOR-2.
2. Develop an improved approach to air defense overflight modeling which will serve as a design framework for future model building.

Chapter 2 contains a description and critique of the air defense model used in VECTOR-2. Chapter 3 contains a

similar analysis for CORDIVEM. Chapter 4 summarizes the major deficiencies found in the analyses. Finally, Chapter 5 presents a generalized approach which addresses the shortcomings of the Vector-2 and CORDIVEM models. The intent of this thesis is not to develop a detailed computer program which will model air defense against overflights. Instead we are developing a program design which can be used to improve current air defense modeling and make the output more credible.

II. VECTOR-2 MODEL ANALYSIS

A. INTRODUCTION

The VECTOR-2 model was developed in 1976 by The Vector Research Corporation. It represents deterministic ground and air theater combat among several kinds of units.

There are three kinds of combat involving aircraft: air to air combat between penetrating attackers and interceptors, ground-to-air attrition against overflying aircraft, and combat in the target area. We will focus on the ground-to-air attrition of aircraft during overflight of the air defense sites.

B. DESCRIPTION OF THE AIR DEFENSE MODEL IN VECTOR-2

1. Overview of the Air Combat Model

In VECTOR-2, aircraft, attacking the same ground target or intercepting the same aircraft, can be placed in the same air group for the duration of the mission. The models of movement and attrition treat all members of an air group as flying together in proximity during the mission. Different air groups fly their missions independently. All air groups marked as "massed" fly together during their missions. During the mission the air group can engage in combat in up to three ways:

- A. It can be attrited by overflowed enemy air defense weapons at any time during its mission .
- B. It can be attrited by air defense fires from air defense sites in the vicinity of the ground target while it is

attacking the target.

C. It can be attrited by interceptors at any time during its flight.

The air combat models pass losses to air groups as they occur during the mission. There are several constraints on these attrition processes. For example, interceptors are assumed never to be exposed to fires from air defense sites and never to be intercepted themselves. An air group follows one of three types of flight paths: straight line, two line segments, or a mass-attack path. The two line segment path consists of a straight line from the base to a turning point, directly across the Forward Edge of Battle Area (FEBA), and a straight line from the turning point to the target. The turning point is on a line perpendicular to the FEBA passing through the target. It is located a certain safe distance behind the FEBA, assumed to be the minimum distance at which the air group is safe from enemy air defense fires. The turning point is chosen in this way to minimize the time during which the attackers overfly enemy air defenses. Figure 2.1 illustrates an attack flight path.

When attack aircraft are massed, one or more air groups fly from their bases to a turning point on their side of the FEBA. There, they turn and fly straight into a massing point on the enemy's side of the FEBA. From the massing point, every air group flies in a straight line to its target, conducts the attack, and flies straight out to its own territory in a path perpendicular to the FEBA. Once it has reached a safe distance behind the FEBA, the air group turns, and flies in a straight line back to its origin. Figure 2.2 illustrates a mass attack flight path.

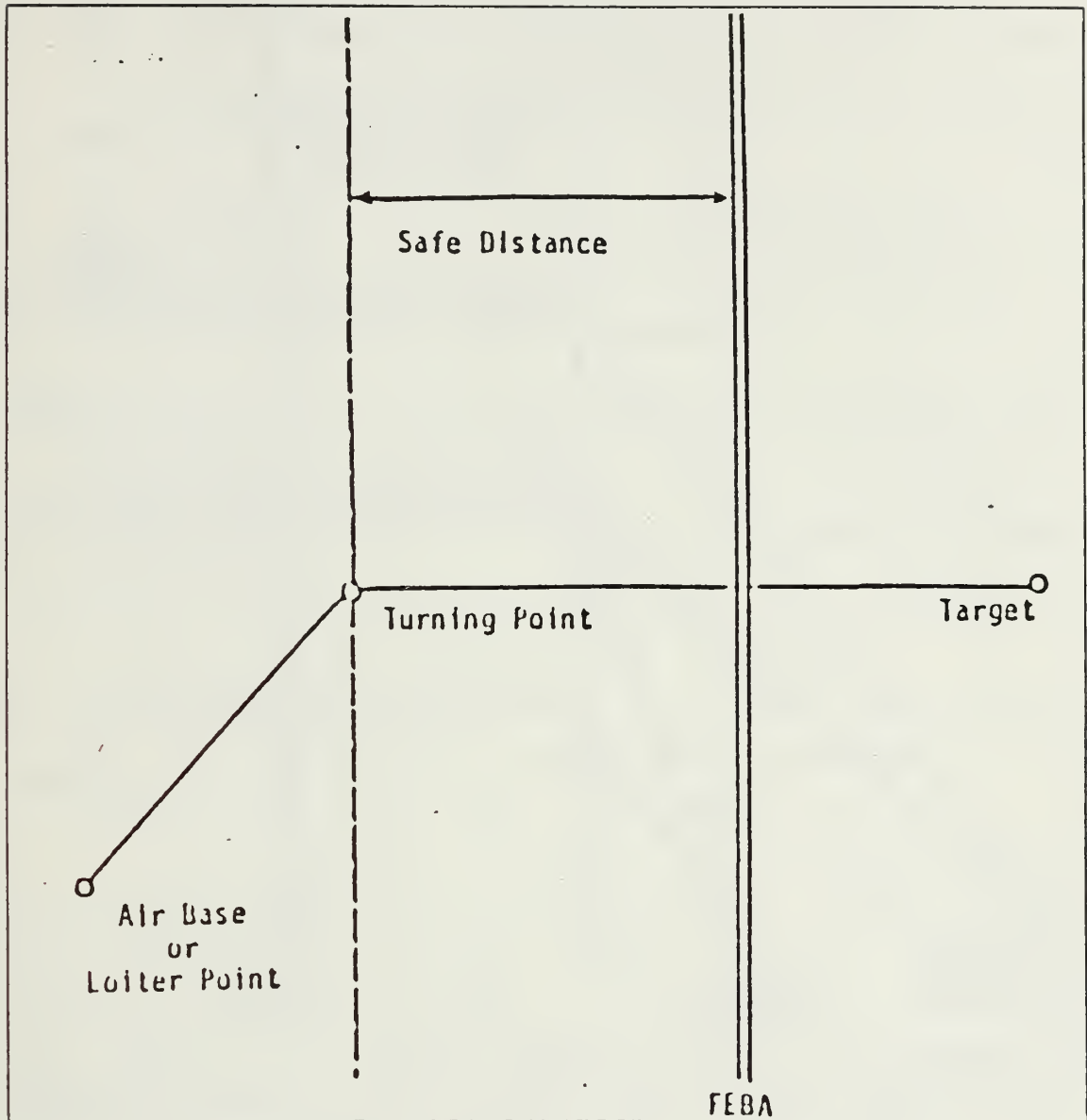


Figure 2.1 Attack Flight Path.

2. Overview of the Ground-to-Air Attrition Model of Overflights

When a penetrating flight comes within range of an air defense site, the air defense weapons at that site have an opportunity to engage the aircraft in the flight. An air

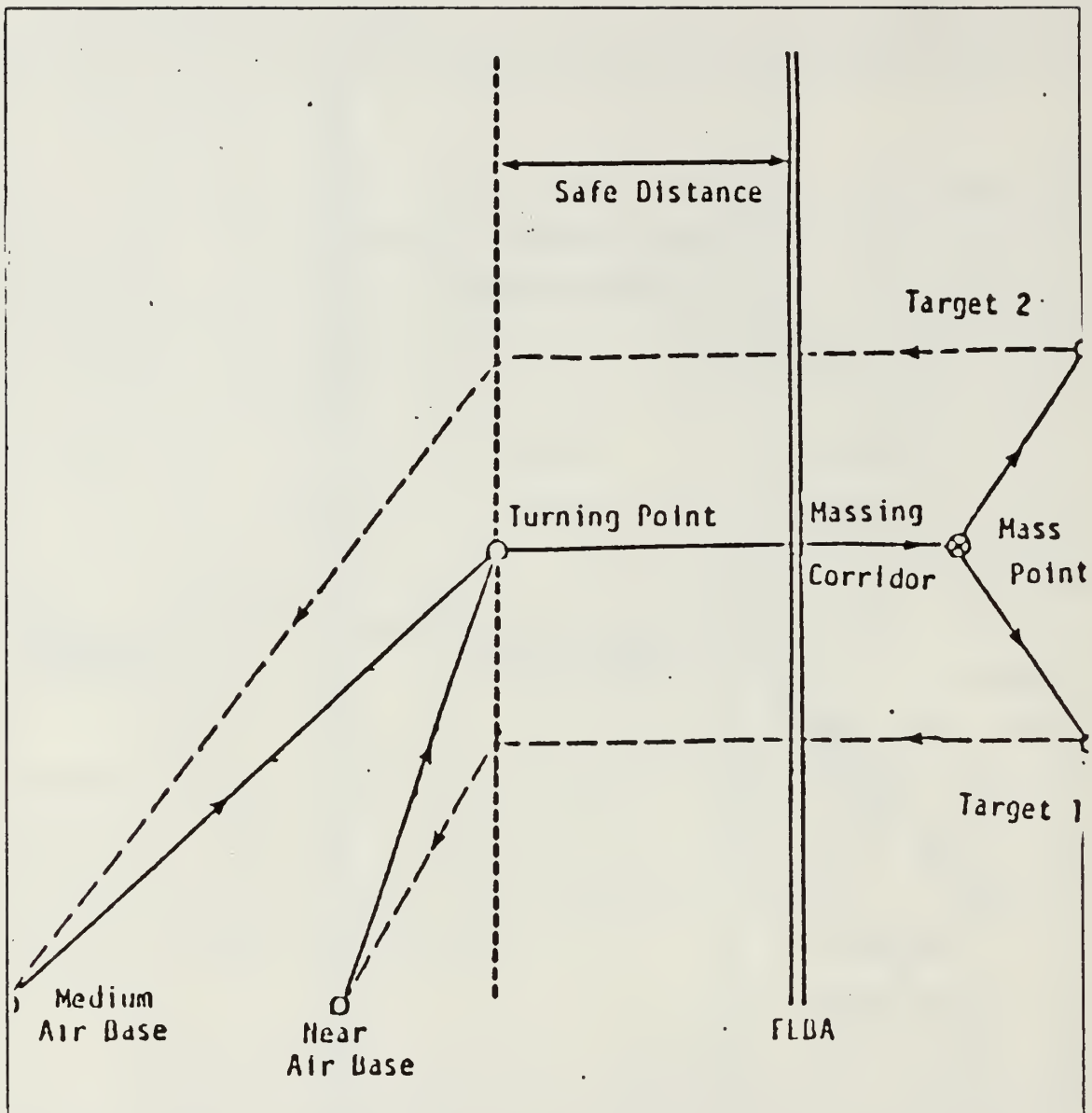


Figure 2.2 Mass Attack Flight Paths.

defense weapon will fire at the aircraft, if all the following conditions hold:

- a. A weapon at the site acquires at least one of the aircraft.
- b. Ordinance is available for the air defense weapon.

- c. The air defense weapon is not occupied engaging other aircraft. Aircraft attacking the site or a ground target in the region of the site are higher priority targets for the air defense weapon than are overflying aircraft.
- d. The air defense weapon is in an ADA resource group. ADA weapons in non-ADA resource groups do not fire at over-flying aircraft. Instead, they fire at aircraft attacking the target they are defending.
- e. The aircraft are not within an intercept corridor, i.e., a region in which interceptors operate and in which air defense weapons are not allowed to fire. If intercept corridors are in effect, air defense weapons may engage aircraft only behind a line located a safe distance behind the FEBA. Forward of this line the air defense function is given exclusively to interceptors. The lateral boundaries of the air defense side's front-line zones consist of straight lines projected perpendicular to the FEBA (see Figure 2.3).

The total losses suffered by an overflying group of aircraft in a time step are the sum of the losses from all fires directed at the group in that interval. The losses caused by a single ADA weapon in that interval, given that the aircraft are within range of the site during the interval, are the product of the rate of fire from the site, the single shot kill probability, and the length of the interval. The firing rate and the kill probability depend on the type of the ADA weapon. The kill probability also depends on the aircraft type.

This attrition model in VECTOR-2 is applied at the start of every time step to compute attrition against air groups in flight during that time step.

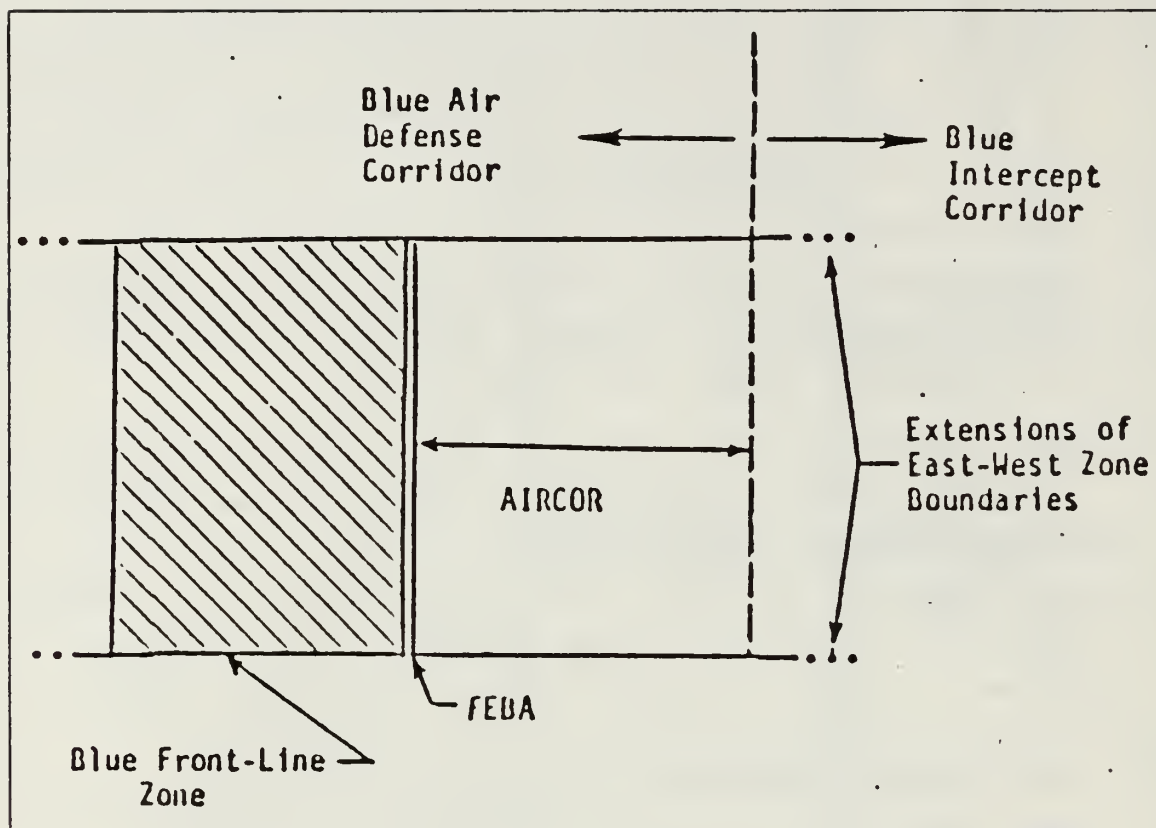


Figure 2.3 Intercept and Air Defense Corridors.

The kill rate computation is based on the following assumptions :

- a. The kill rate against aircraft in a particular group is the sum of the kill rates from the air defenses of all different zones.
- b. The kill rate against a particular type of aircraft in a group is determined using the assumption that the rounds fired against the group have equal probability of being fired against any aircraft in the group.

The losses to type k aircraft in air group L during an interval of length Δt are:

$$n_{kL} = \sum_i \sum_j m_{ij} a_{ijkL} \Delta t$$

where

n : the number of aircraft.

m : the number of ADA weapons.

m_{ij} : the number of air defense sites of type i in zone j that are not suppressed, are not allocated to fire at aircraft attacking the site or targets around it, and have ammunition available.

a_{ijkL} : the average rate at which such a type i ADA site in zone j is killing type k aircraft of air group L during this time step.

3. The Kill Rate

The kill rate is the average rate at which aircraft are attrited during the entire mission. It is the total expected ADA attrition of the group, divided by the duration of that part of the mission when the group is vulnerable to ADA fire. Thus, the attrition of the group is "smoothed" over the vulnerable period and is not necessarily assessed in the actual amounts received at the time the attrition occurs. This averaging of the kill rate avoids the repetition of many costly calculations in each time step.

The rest of this subsection is concerned with computing the kill rate.

The kill rate for a type i ADA in zone j versus type k aircraft in group L is given as follows:

$$a_{ijkL} = f_{ijL} b_{iL} r_i q_{ik} \left(\frac{n_{kL}}{\sum_x n_{xL}} \right) e_{ij} c_L E_{iL}$$

The factors of this equation are defined below.

f_{ijL} : the fraction of type i ADA sites in zone j which are within range of air group L for some part of its mission. It is determined from the flight path and altitude of the air group and by the range of this type of ADA site.

b_{iL} : the average fraction of time, while an air group is in range of an ADA site, that it is acquired and can be engaged by the site.

r_i : the average firing rate of a type i ADA site against overflight aircraft, given that it is engaging overflying aircraft.

q_{ik} : the probability of kill per unit of fire for type i ADA site engaging type k aircraft on overflight.

e_{ij} : the proportion of the fire which a type i ADA site in zone j actually achieves against the group, considering the current saturation of the site by multiple flights. Thus, given that an air group is an eligible target, this is the probability that the ADA site is not engaging some other target.

c_L : the probability that any given ADA site is allocated to fire at air group L, given that the air group is currently eligible to be fired at by the site. This factor reflects assumed restrictions in ADA fire, whereby an average of one site may fire per every two aircraft in the group.

E_{iL} : the fraction of the vulnerable period in which

the air group is within range of a given ADA site, given that it passes within range of the ADA site during some time vulnerable period of its mission.

$$\frac{n_{kL}}{n_{xL}} : \text{The ratio of the number of aircraft of type } k \text{ to the total number of aircraft. It appears as a factor to allocate fire with equal probability over all aircraft in the group.}$$

4. The Saturation Factor

The factor e_{ij} was interpreted as the probability that a type i ADA site in zone j is engaging an air group, given that the air group is in range and available as a target. This is just the reciprocal of the mean number of air groups available as targets, given that at least one is available. Thus, the saturation factor is given by the equation

$$e_{ij} = \frac{1 - \&_{ij}}{u_{ij}}$$

The numerator is the probability of at least one air group being available, and the denominator is the unconditional mean number of air groups available at one time. The probability that no target is available is

$$\&_{ij} = \prod_L \left\{ 1 - f_{ijL} b_{iL} c_L E_{iL} \frac{t_L}{T_L} \right\},$$

where the product extends over all air groups, and where

t_L : the integration period ; i.e., the duration of the

period during which the model will assess attrition against air group L .

T_L : the duration of the mission of group L, from take-off to landing.

The duration of the mission is estimated from the known length of the flight path, the known air group speed, and the assumption that an input maximum number of passes will be made over the target. The integration period approximates the vulnerable period of the air group, but accounts for the fact that an integer number of time steps will be taken by Vector-2 to assess the attrition in the vulnerable period.

The mean number of air groups available at one time, as targets to a single type i ADA site in zone j, is

$$u_{ij} = \sum_L c_L b_{iL} E_{iL} \left(\frac{S_{iL}}{T_L} \right) ,$$

where

S_{iL} : the minimum of M_{iL} , the mean time spent within range of an ADA site of type i, and the vulnerable period of group L.

The mean time in range of a type i ADA site is obtained by approximating the region around an ADA site in which the site can engage aircraft by a rectangular area. The lateral range (along the earth's surface) of a type i ADA site against air group L is

$$L_{iL} = (R_i^2 - A_L^2)^{1/2} ,$$

if $R_i > A_L$, where

R_i : the slant range of a type i ADA site .

A_L : the altitude of air group L .

The region around the site where air group L could be engaged is approximated by a rectangle of width $2L_{jL}$ and depth $L_{jL}/2$, so that the area around the site is preserved to be that of a circle of radius L_{iL} .

It is assumed that ADA sites are located no closer to the FEBA than a line a distance $L_{iL}/2$ behind and parallel to the FEBA. Denote the length of the flight path from this line to the target of group L by the symbol P_{iL} .

Let r denote the average speed of the air group.

Three cases can hold, as defined below.

If $P_{iL} \geq L_{iL}/4$, then

$$M_{iL} = \frac{\pi L_{iL}}{r} \left(1 - \frac{\pi L_{iL}/4}{P_{iL} + L_{iL}/4} \right) .$$

If $-\pi L_{iL}/4 < P_{iL}/4$, then

$$M_{iL} = (P_{iL} + \pi L_{iL}/4)/r .$$

If $P_{iL} < -\pi L_{iL}/4$, then

$$M_{iL} = 0 .$$

5. The Coordination Factor

The factor C_L is the probability that any given ADA site is allocated to fire at an aircraft in group L, given that the air group is currently eligible to be engaged by the site. The specific form of this factor used in VECTOR-2 was derived from an assumption that no more than one site on the average may fire at every two aircraft in the group.

Two physical situations are of particular interest as alternative interpretations of this assumption. First, is the situation in which air defense sites are assigned non-overlapping regions of air space. then, a site can engage only aircraft inside its own assigned region. These regions need not cover the entire air space. But, as long as aircraft travel in pairs, each pair of aircraft can be in the region of no more than one ADA site at a time. Second, is the situation in which ADA sites are not assigned physical regions of responsibility, but in which their fire is coordinated by a central facility. This facility allocates targets to specific sites. The coordination factor reflects a case in which the allocation controllers assign an average of no more than one site to every two aircraft.

The coordination factor is computed as the ratio of (1) the maximum number of weapon-seconds of fire that could be directed at the group during its mission, if fire is restricted to one site per pair of aircraft, to (2) the number of weapon-seconds of fire that could be directed at the group if no such restriction exists.

Thus, the factor is

$$C_L = \frac{.5 T'_L \sum_k n_{kL}}{\sum_i t'_{iL} \sum_j f_{ijL} m_{ij}}$$

where

T'_L : the duration of the vulnerable period for air group L; i.e., the length of time that the group is over enemy territory or within ADA range of enemy territory.

t'_{iL} : the mean time that group L spends within range of a type i ADA site, given that it comes within range of the site at some time in the vulnerable period.

6. The Exposure Factor

The factor E_{iL} is the fraction of the integration period in which the air group is within range of a given ADA site, given that it passes within range of the site at some time during the group's mission. It is simply

$$E_{iL} = \frac{S_{iL}}{t_L}$$

where the numerator and denominator have both been defined previously.

C. MAJOR DEFICIENCIES OF THE VECTOR-2 AIR DEFENSE MODEL

The VECTOR-2 model contains several deficiencies which raise doubt about the accuracy of predicted aircraft attrition rates. These deficiencies are documented in this section.

1) The model does not consider the earth curvature effect.

Consider the case of a typical flight, as in Figure 2.4.

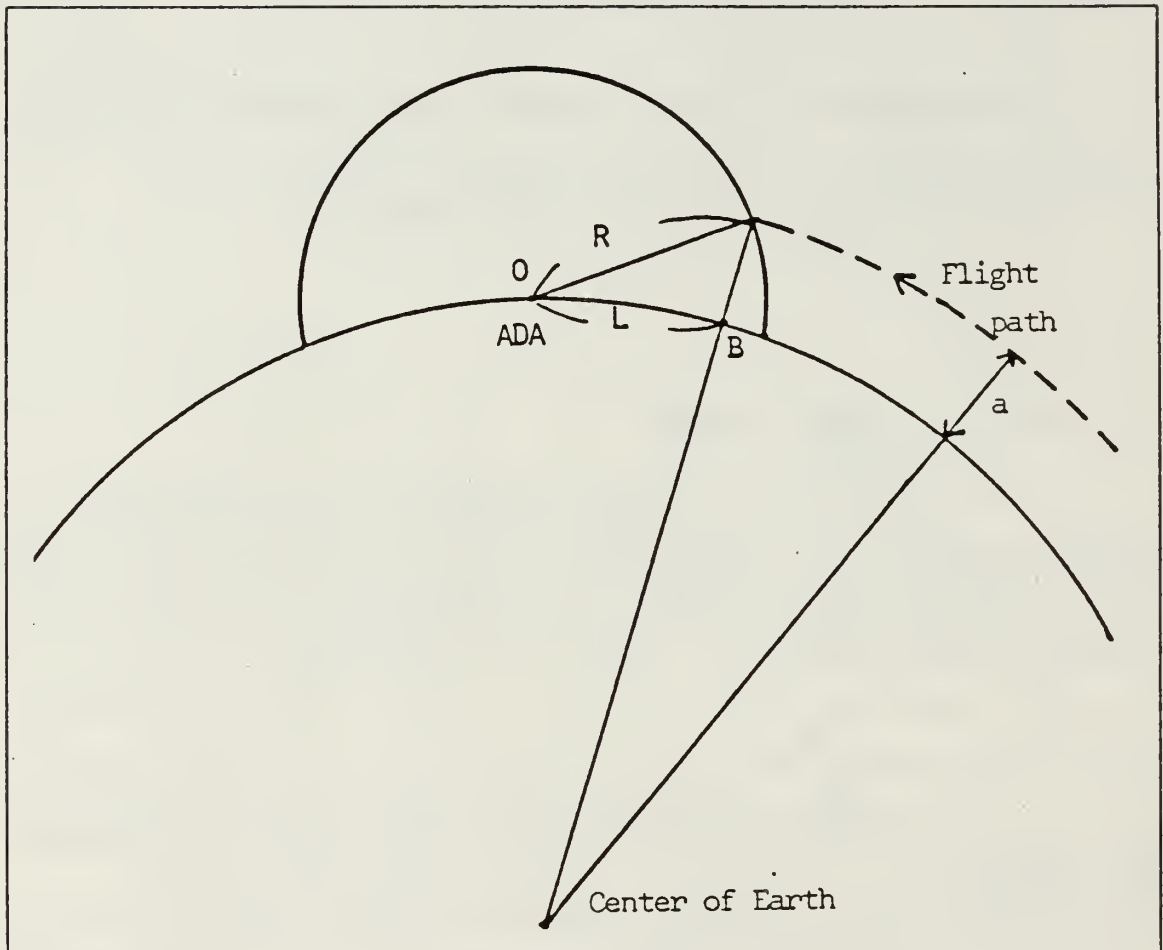


Figure 2.4 VECTOR-2 Lateral Range Calculation.

The VECTOR-2 model defines the lateral detection range (distance along the earth's surface) as the length of the curve segment OB. The algorithm computes an approximation for lateral range, L , as follows:

$$L \approx (R^2 - a^2)^{1/2}$$

Where R = Maximum range of the ADA acquisition radar.
 a = Altitude of the aircraft.

This approximation is poor for low altitude aircraft flying below the radar horizon. Figure 2.5 shows an example of a low flying aircraft.

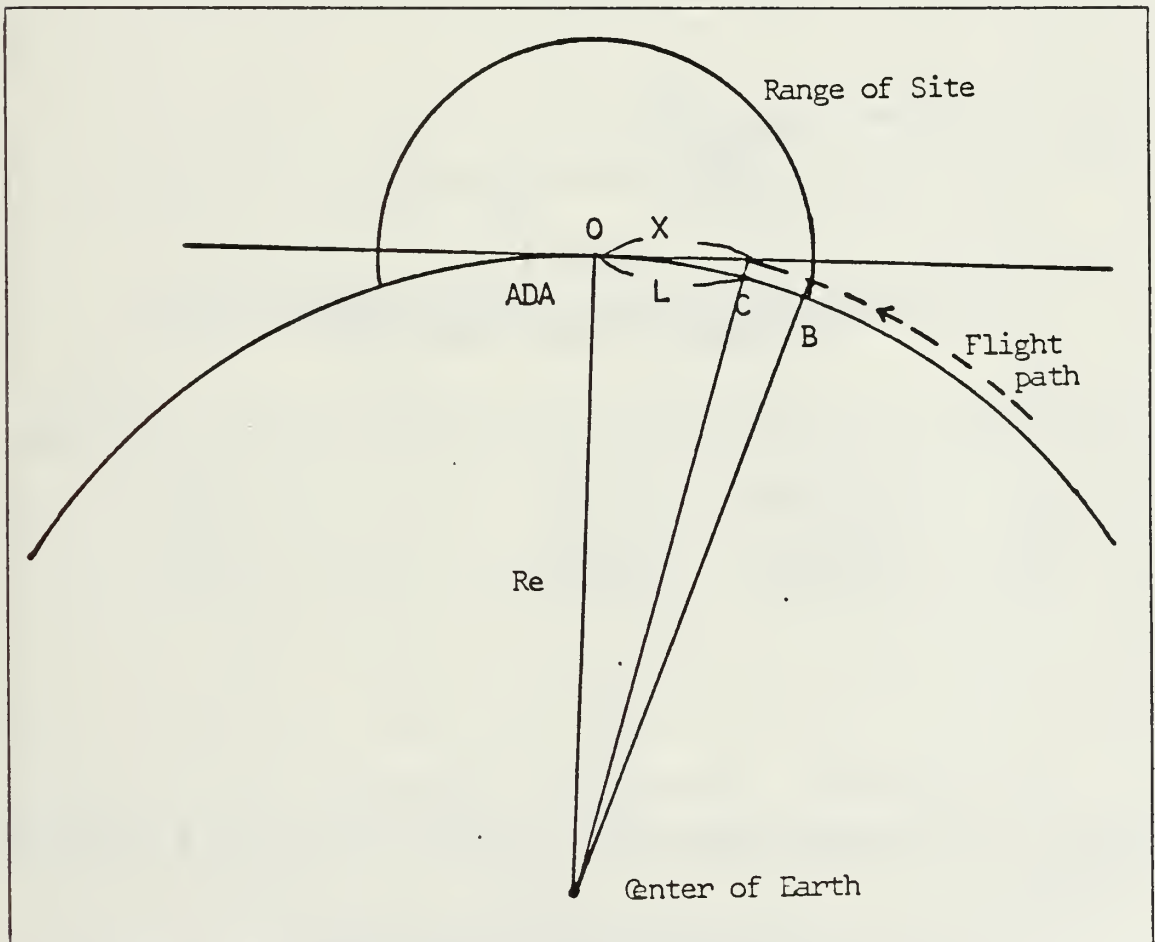


Figure 2.5 The Flight Paths Considering Earth Curvature.

An improved approximation for lateral range can be derived in the following manner.

Let X = The slant range of the target at detection.

R_e = Radius of the earth.

$$\text{Then } X = \left((R_e + a)^2 - R_e^2 \right)^{1/2} = \left(a^2 + 2aR_e \right)^{1/2},$$

$$\text{for } X \leq R$$

$$\text{Since } L \approx \left(X^2 - a^2 \right)^{1/2}$$

$$\text{then } L \approx \left(2aR_e \right)^{1/2}.$$

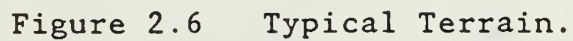
TABLE I
A COMPARISON OF LATERAL RANGE APPROXIMATIONS
CONSIDERING EARTH CURVATURE

| a (feet) |	| X (miles) |	| L (Vector-2, miles) |	| L (modified, miles) |
| 4500 |	| 82.59 |	| 59.99 |	| 59.99 |
| 1000 |	| 38.93 |	| 59.99 |	| 38.92 |
| 500 |	| 27.52 |	| 60.00 |	| 27.52 |

As an example, compare the approximations of lateral range for different altitudes. Assume the value of R equals 60 miles.

For an aircraft flying at 1000 feet above the surface of the ADA site, the lateral range was overestimated by more than 20 miles. This overestimation can greatly overstate the detection capability of the site.

This model does not consider the effect of terrain masking. Yet, terrain can be the most significant factor affecting the acquisition and engagement of an aircraft. For example, consider the terrain profile shown in Figure 2.6.



The distance between the ADA site and the obstacle, l , is 15 miles. The height, h , is 500 feet. If an aircraft is approaching the site at an altitude, a , of 500 feet, the true lateral range of the aircraft, L_2 , is 15 miles. Table II compares the lateral range approximations without terrain masking, where

L = lateral range computed in VECTOR-2

L_1 = lateral range computed considering earth curvature correction.

TABLE II
A COMPARISON OF LATERAL RANGE APPROXIMATIONS
CONSIDERING TERRAIN

a (feet)	L (miles)	L_1 (miles)	L_2 (miles)
500	60.00	27.52	15.00

From the above comparison, it is clear that lateral range calculations can be easily overestimated when terrain effects are ignored.

3) The model does not consider the case of overlapping coverage.

The VECTOR-2 model assumes that no more than one site, on the average, may fire for every two aircraft in the group. This assumption is reasonable in two different situations. The first situation occurs when air defense sites are assigned non-overlapping regions of air space. The

second situation occurs when the fire of ADA sites is coordinated by a central facility that allocates a target to a specific firing unit. However, ADA site coverages are often overlapped. Furthermore, it is very difficult to coordinate the fires of ADA sites under battle conditions when communication may be degraded. Therefore, if the ADA sites are positioned so that overlapping coverage exists, the model will overestimate the attrition of aircraft.

4) The model does not consider enemy electronic warfare (EW) capability.

There should be time delays inserted in the acquisition and tracking models to simulate the effectiveness of enemy EW against the air defense system. These time delays can be modelled as random variables which are dependent on the type and number of EW systems acting against the ADA sites in question.

5) The model does not allow sites to exercise target prioritization and selection.

A primary model assumption is that a site will distribute fires uniformly over all targets which are within radar coverage. This violates basic air defense doctrine. Sites should fire at targets inbound to the defended area before firing at targets which are returning to their side of the FEBA.

6) The model assumes that a given site uses a constant rate of fire.

The rate of fire of an air defense weapon is strongly dependent on the continuity of the acquisition and tracking process. If terrain effects are ignored and the lateral range of acquisition is merely a function of flight altitude, the firing rate can be grossly overestimated.

7) The model does not allow for fratricide.

In most air defense scenarios, fratricide is reality which cannot be avoided. There should be some consideration given to the loss of time and weapon allocation resources which result when a site fires on friendly aircraft.

8) The aircraft movement algorithm is highly restrictive.

The description of aircraft movement in VECTOR-2 indicates that all the aircraft in a flight pass through site radar coverage envelopes at constant altitude and speed. Such tactics would rarely be employed by overflying aircraft as they approach their intended targets. The enemy aircraft approaches should allow for more realistic routes.

9) The input variables used to calculate the kill rate represent average system/operator performance characteristics. Terrain effects, command and control policies, and enemy electronic warfare capabilities have not been explicitly considered in determining these averages. The kill rate is computed by multiplying these variables. Specifically, the kill rate formula is of the form

$$a_{ijkL} = f_{ijL} * b_{iL} * r_i * q_{ik} * \left[\begin{array}{c} \text{etc.} \\ \end{array} \right]$$

Where

f_{ijL} : the fraction of type i ADA site in zone j which are within range of air group L for some part of its mission.

b_{iL} : the average fraction of time, while an air group is in range of an ADA site, that it is acquired and can be engaged by the site.

r_i : the average firing rate of a type i ADA site against overflight aircraft, given that it is engaging overflying aircraft.

q_{ik} : the probability of kill per unit of fire for type i ADA site engaging type k aircraft on overflight.

The kill rate is the dominant factor in computing aircraft attrition. It is strongly influenced by the multiplication of the above four variables which are derived from aggregate methodology. Therefore, the kill rate can have a large variation when there are small errors in each factor. In particular, a 5% error in each factor results in approximately a 20% error in the overall kill rate prediction.

III. CORDIVEM MODEL ANALYSIS

A. INTRODUCTION

The air defense model used in CORDIVEM has many of the same aggregate features of VECTOR-2. This chapter will describe the main features of the overflight model and summarize major deficiencies existing in the model design.

High resolution techniques were employed to develop aggregate factors as inputs to the CORDIVEM air defense model. In particular, a model run by the Army Material Systems Analysis Agency (AMSAA) was used to generate variables such as average acquisition range and probability of kill. The model, known as INCURSION, is a one-on-one air defense simulation which has been employed for several years. This method of providing aggregate model inputs is superior to that of VECTOR-2. However, there is still a considerable loss of realism. In general, the problems of aggregation still exist.

B. DESCRIPTION OF THE AIR DEFENSE MODEL IN CORDIVEM

1. Fraction of Engagement (FRACEN)

In the air defense submodel of CORDIVEM, the primary values of interest appear to be average engagement range, probability of kill, and average number of rounds expended. The quantity of average engagement range seems especially important, since it is the value used throughout the air defense submodel to determine if an engagement is possible. This variable is an output of the ADAGE INCURSION model which produces the results of a one-on-one duel between an air defense system and a single aircraft. In ADAGE

INCURSION, two types of flight paths are considered: a straight line ingress / egress and an attack pattern in the target vicinity.

Since ADAGE INCURSION is a stochastic simulation, a large number of trials must be performed to obtain statistically significant results. Each trial varies the lateral offset of the flight with respect to the air defense system, as well as providing different random draws which affect probabilistic system functions. After the completion of the requisite number of trials, summary statistics can be compiled for the flight path.

The calculation of FRACEN depends on a flight path. For ingress / egress flight paths,

$$\text{FRACEN} = \frac{\text{Distance That The Flight is in Acquisition}}{2 * \text{Average Engagement Range}}$$

From this equation, the FRACEN can equal 1 only if the flight flies directly over the air defense system. But the average engagement has that flight path as being a special case with offset being equal to zero. For an in-target-vicinity flight path,

$$\text{FRACEN} = \frac{1}{\text{Pass Number}}$$

This causes a counter-intuitive result. As more passes are made on a target, the air defense becomes less and less effective. For each trial of an attack pass, only one pass should be modeled. There are no multiple passes allowed. Since the engagement results match up the single run shown in INCURSION, each pass should have FRACEN = 1. But under the assumption that the entire attack pass is

constrained in the airspace over the single hex, this formula is applied.

2. Time for Engagement (RMINTIM)

This algorithm is used to check on the passage of inter-engagement time. Before an AD unit is allowed to engage a flight, some amount of time must pass since the previous engagement of this ADA unit.

$$\text{RMINTIM} = \text{Time Between Engagement} * \text{FRACEN}$$

Here, the time between engagements is a function of the air defense system itself. The major assumption here is that the time between engagements will degrade linearly with FRACEN. This assumption obviously does not hold at values of FRACEN close to zero, since there must be some minimum time needed for an engagement process.

3. Maximum Number of Firers (RMAXF)

$$\text{RMAXF} = \frac{\text{Number of AD Weapons in Unit}}{\text{Number of AD Weapons Engaging Flight}}$$

It is assumed that AD firings are uniformly distributed over the flight to be engaged. The concept of prioritization is ignored. Also, factors such as perceived threat to the fire unit or defended asset and battlefield geometry are not considered.

4. Number of ADA Systems Available for Firing (RNADA)

The availability of ADA system during an engagement can be expressed as:

$$\begin{aligned} \text{RNADA} &= \text{Maximum number of Firers (RMAXF)} \\ &\quad * \text{Probability of Participation (ROBP)} \\ &\quad * \text{Fraction of an Engagement (FRACEN)} \\ &\quad * \text{Percent of unit's coverage area covered} \\ &\quad \text{by one Weapon (RPERCOV)} \end{aligned}$$

The probability of participation is the result of a look-up table, based upon the function of the AD weapon, the aircraft type, and the participation index. This table is taken from ADAGE CAMPAIGN and represents the level of participation one could expect from an aggregated AD unit.

A single ratio is given as follows:

$$\text{RPERCOV} = \frac{\text{System Coverage}}{\text{Unit Coverage}}$$

Here, the system coverage is represented by a circle of radius equal to the average engagement range. It is assumed that the number of units available for an engagement will be based on the ratio of coverage areas without consideration of engagement geometry.

5. Number of Weapons Needed (RNADN)

The algorithm is

$$\text{RNADN} = \frac{\text{Number of Aircraft in Flight/ Pka}}{\text{Number of Simultaneous Engagements per Weapon}}$$

This term could be considered as a fire control measure since it determines the minimum number of AD systems

required to completely destroy the flight using an A-kill criteria. An A-kill is damage inflicted on an aircraft which causes its destruction within a five minute period. The term in the denominator indicates a preference for simultaneous engagements by a single weapon in lieu of multiple engagements by various weapons. Most fire control systems would favor utilizing as many assets as possible before resorting to extended simultaneous engagements.

6. Number of Fully Supplied Weapons (RNADSS)

$$\text{RNADSS} = \frac{\text{Rounds left in Unit}}{(\text{Number of Simultaneous Engagements / Weapon}) * (\text{Rounds / Engagement})}$$

Supply considerations are of greatest import for this algorithm. The level of aggregation in CORDIVEM precludes consideration of weapons firing with less than the average number of rounds required.

7. Number of Aircraft Affected by AD (RNACN)

$$\text{RNACN} = \text{Number of Weapons Firing} * \text{Number of Simultaneous Engagement / Weapon}$$

After the number of weapons to fire in this engagement has been determined, subroutine ACDIE can calculate the number of aircraft that will be affected by the air defense. This algorithm again assumes no shared targets among the AD weapons taking part in the engagement.

8. Number of Aircraft Surviving Kill (RNACSK, RNACSKA)

This algorithm provides two different formulas depending upon the type of AD system involved in the engagement. First, for HIMAD weapon systems

RNACSK = Number of A/C in Flight

- Pk * Number of A/C Engaged.

For this formula, two assumptions are important:

- a. Only one HIMAD weapon per site fires at a given flight. For a large flight, this would probably not hold but it is acceptable for the present play of two to four aircraft per flight.
- b. The number of simultaneous engagements per weapon will not exceed the number of aircraft in the flight. It means that the HIMAD weapon will only fire one missile at each aircraft in the flight per engagement. So no multiple engagements of the same aircraft will take place.

There is also no accounting for shared kills by multiple AD units against the same flight.

For SHORAD weapon systems

RNACSK = Number of A/C in Flight

- Pk * Number of A/C Engaged

Both of these formulas ignore the problem of shared kills. It is possible for one aircraft to be engaged by more than one firing unit. As a result, these algorithms overestimate attrition rates.

C. MAJOR DEFICIENCIES OF THE CORDIVEM AIR DEFENSE MODEL.

1. In this model, the kill rate is also formed by multiplying several factors. As a result, it is very sensitive to small errors in input variables.
2. This model does not allow for degradation of detection capability because of terrain and earth curvature effects.

3. In the algorithm which computes FRACEN for an in-target-vicinity flight path, FRACEN is the reciprocal of pass number. This implies that as more passes are made on a target, the air defense becomes less effective. If there are no multiple passes allowed, only one pass would be modeled and each pass should have $\text{FRACEN} = 1$. As such, the formula is meaningless in the one pass algorithm. In reality, FRACEN would probably increase on subsequent attack passes due to the lessened detection and reaction times for the air defense system. Additional ADAGE runs could explore this possibility and develop a factor to be applied to all attack passes after the initial one.

4. In maximum number of firers (RMAXF), The concept of prioritization is ignored. There is no greater emphasis on four helicopters firing ATGM than two penetrators egressing over their area. Presently this algorithm would allocate ADA units equally to each threat.

5. In number of AD systems available for firing (RNADA), the availability of AD systems during an engagement is a function of four terms: the maximum number of firers (RMAXF), probability of participation (ROBP), fraction of engagement (FRACEN), and percent of unit's coverage area covered by one weapon (RPERCOV). The number of units available for engagement is based on the ratio of coverage areas without consideration of engagement geometry. However, geometry affects this algorithm much more than any of the terms mentioned.

6. In number of weapons needed (RNADN), it is unlikely that any fire control system would consider total attrition of a flight with an unlimited number of AD systems. Furthermore, this algorithm does not consider shared kills between AD systems. The possibility of multiple kills should be modeled.

7. There is presently no structure in the air defense submodel to portray command and control issues. Weapons control status manipulation and fire distribution can be major determinants in the conduct of an air defense battle. Furthermore, this model does not consider overlapping coverage by two or more ADA sites. In order to optimize the use of air defense assets, CORDIVEM should include fire control and account for overlapping coverage.

8. Fratricide can not take place in this air defense model. Some means of portraying fratricide for the air space management measures should be included in this submodel.

9. The effects of enemy aircraft ECM on radar capabilities should be played explicitly in this submodel. The effects of jamming, terrain-following flight paths, and other countermeasures could be modeled through manipulation of the minimum engagement time and the attrition rate.

10. Air defense units must be allowed to prioritize their fires when faced with multiple targets. The model does not allow for prioritization and logical target selection by each site.

11. The model does not allow for overkill. Overkill should be acceptable against a target identified as threatening a critical asset.

12. The determining factor in the calculation of FRACEN in subroutine ACDIE should be time rather than distance. A more realistic method of attrition can then be based on time in coverage rather than distance in coverage.

13. An air defense weapon can have either an optical mode or a radar mode in this submodel. Therefore, it is necessary to consider the systems as having two acquisition modes.

14. Smoke must be considered for units which depend upon optical means of acquisition in this submodel because it can have an effect upon both the acquisition and weapon performance portions of an engagement.

IV. SUMMARY OF ANALYSIS

The review of the air defense models contained in VECTOR-2 and CORDIVEM has demonstrated that aggregate modeling of air defense engagements has several shortcomings. These shortcomings are summarized below.

A. ENGAGEMENT GEOMETRY

Terrain and earth curvature effects have been generally ignored. It is possible that low flying aircraft could spend minimal time in air defense coverage envelopes and have a very high probability of survival.

B. COMMAND AND CONTROL

Command and control is not modeled in any manner. If the air defense units are operating in a centralized mode, fire distribution may be very efficient. However, it will also be very time consuming. The net result of this type of control cannot be easily examined using aggregate modeling. If the air defense units are operating in a decentralized or autonomous mode, time delays will lessen. However, shared kills will increase and the attrition rate may be overestimated.

C. ELECTRONIC WARFARE

There is no allowance for degraded system/operator performance when enemy aircraft have electronic countermeasures (ECM) available. A mediocre air defense crew can be rendered ineffective in a hostile electronic environment. The model user should have the option to input enemy ECM capability into the air defense battle.

D. TARGET PRIORITIZATION AND SELECTION

Individual firing units rarely distribute fires uniformly over the threat. Air defense models should provide for fire unit prioritization and selection. There should also be provisions for the time delays which may occur in order to accomplish these tasks.

E. INTERMITTENT SYSTEM/OPERATOR FAILURES

The engagement sequence of detection, acquisition, track, fire, and damage assessment must be modeled in the light of highly variable levels of performance. Both air defense systems and operators will not repeatedly perform at the same degree of proficiency. Such variabilities should be incorporated to make the attrition analysis credible.

F. FRATRICIDE

The engagement process should allow for the uncertainties and time delays which will occur when a firing unit is required to identify targets as friend or foe (IFF). It is unrealistic to assume that fratricide will not occur or that IFF procedures are carried out without time delays.

The following chapter will present the design of a modeling approach which addresses the above shortcomings. This model will more accurately portray the air defense process and prevent the user from inputting model parameters which are heavily biased or inadvertently misleading.

V. GENERAL APPROACH TO MODELING AIR DEFENSE AGAINST OVERFLIGHT

A. INTRODUCTION

The purpose of this chapter is to present an air defense simulation design which will eliminate many of the modeling deficiencies documented in the preceding chapters. The proposed approach will make use of higher resolution techniques. However, many of the calculations and submodels can be implemented in an off-line mode. In most cases, these subprograms can be executed in a pre-processing stage and will have negligible effect on the execution of the main simulation.

An overview of the air defense engagement sequence will be presented. This sequence will provide the framework used to develop the simulation design. This design is intended to provide an architecture for the model builder. Emphasis will be placed on modeling terrain, ECM, command and control, and system/operator performance. Details on the submodels accessed by the main program are developed in the appendices following Chapter VI.

B. MODEL ASSUMPTIONS

The assumptions which the model design has used are:

1. Aircraft flight paths can be modeled as series of connected line segments.
2. Enemy aircraft will employ terrain masking as tactics dictate.
3. Enemy aircraft may employ ECM to enhance their probability of survival.

4. Air defense sites will operate in both centralized and autonomous modes of control.
5. Air defense sites will be located as tactics dictate. The locations will allow for overlapping coverage to defend high priority targets.
6. Each air defense site has some maximum number of targets which it can engage.
7. There will be a one-to-one correspondence between active tracking radars and targets which are being tracked.
8. Each air defense site will follow a designated target prioritization and selection algorithm.
9. Fratricide can occur. If IFF checks are used, probabilities of erroneous target classification will be assigned.
10. Intermittent system/operator failures will be allowed.
11. Inclement weather conditions will degrade system performance.

C. DESCRIPTION OF THE ENGAGEMENT SEQUENCE

An air defense site follows a well defined engagement sequence as it attempts to destroy enemy aircraft. The steps of the sequence are:

1. Detection - The system/operator senses the presence of an aircraft in the assigned airspace.
2. Track - The site tracking radars obtain radar lock on the target.
3. Fire - The site launches a missile attempting to destroy the target.
4. Intercept - The missile arrives at a predicted point in space. This point is assumed to be the location of the collision of the missile and the target.

5. Damage Assessment - The system/operator decides if target destruction has been achieved.

These steps are illustrated in Figure 5.1.

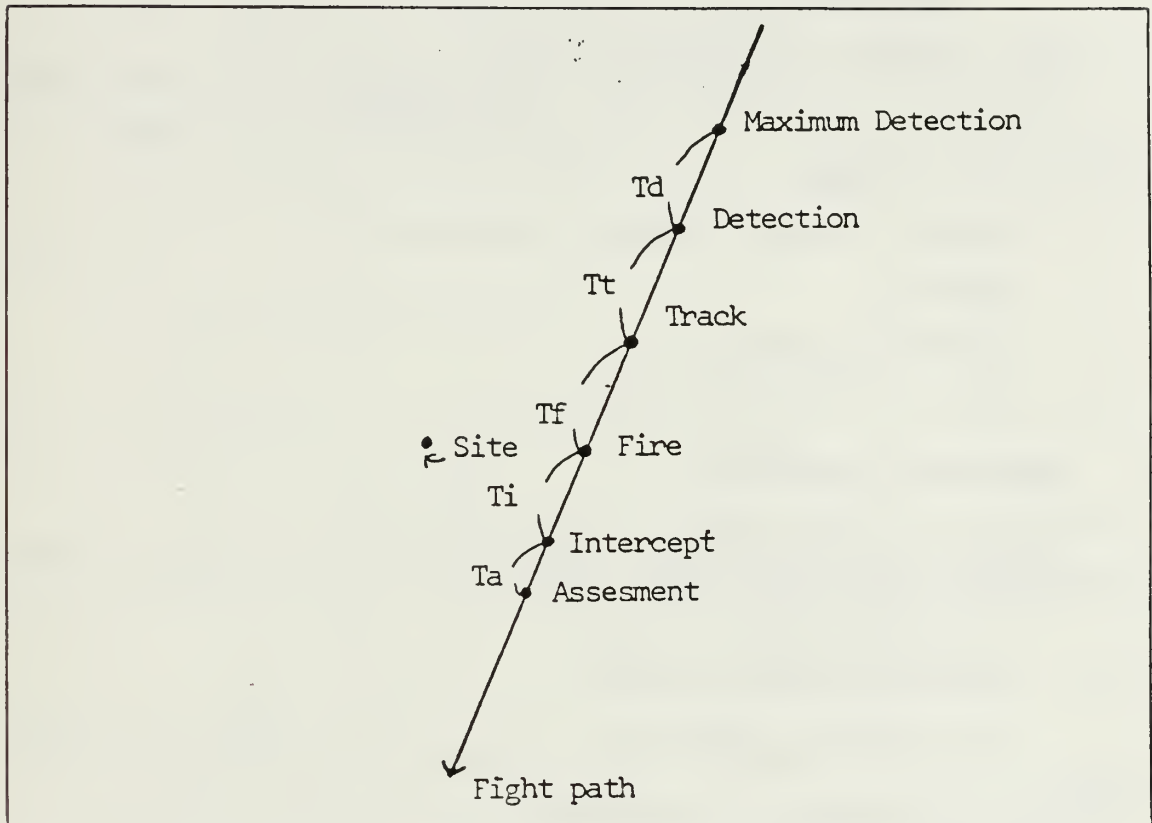


Figure 5.1 The Engagement Sequence.

If the target leaves radar surveillance (either acquisition or tracking), the sequence is terminated. When the target returns to the site detection envelope, it is considered to be new acquisition. The time delays associated with each step of the sequence are defined as follows:

T_d = time between maximum possible detection and actual detection.

T_t = time between actual detection and track.

Tf = time between track and fire.

Ti = time between fire and intercept.

Ta = time between intercept and assessment of the intercept.

The proposed model design will explicitly model these time delays. The time delays are generally a function of four major factors:

1. Normal system/operator variability
2. Weather
3. Enemy ECM capability
4. Mode of Control

D. MODEL PRE-PROCESSING

Several pre-processing submodels will be used to make the model design more efficient.

1. Pre-Processing Inputs

The inputs required by the pre-processing submodels are:

- a. Site location in term of its map grid coordinate, X and Y.
- b. Site altitude, s.
- c. Acquisition/tracking radar maximum slant range, R.
- d. Target flight path description (see Appendix A):
 - 1) Initial position and time of departure.
 - 2) Heading, distance, speed, and altitude of each flight segment.

This path description will be used to generate a target flight model, $(X(t), Y(t), a(t))$, where,

- a) $X(t)$ and $Y(t)$ are the target grid coordinates at time step, t , and
- b) $a(t)$ is the target altitude at time step, t .

e. Average altitude grid (see Appendix B).

This will be used to generate a minimum altitude grid (Appendix C).

f. Missile flight model.

This will be used to determine a predicted intercept point when a missile is fired at the target.

2. Pre-Processing Outputs

The objectives of pre-processing are to:

- a. Generate a detection state vector for each site.
This state vector is used to determine if a target is capable of detection during a time step.
- b. Generate an intercept state vector for each site.
This state vector is used to determine if a missile should be fired at a target during a time step.
- c. Generate a priority state vector for each target.
This state vector determines whether the target is in the attack or return portion of its flight path during a time step.

These state vectors will become part of the input for the simulation model design.

E. OVERVIEW OF THE MODEL DESIGN

In this section we will discuss a general description of the model design. A flow chart of the model is shown below.

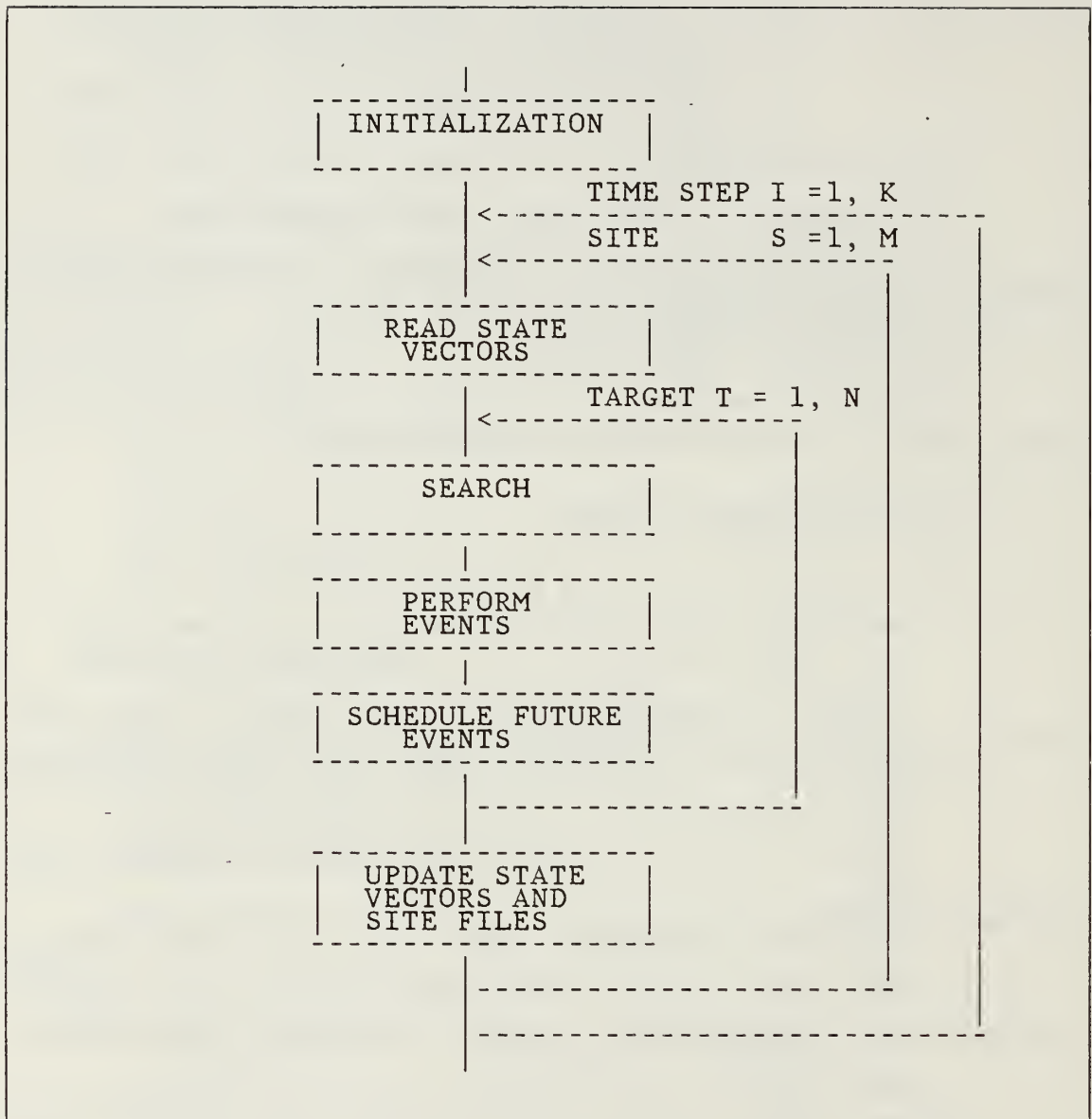


Figure 5.2 Model Flow Chart.

1. Initialization

The model will be initialized with the following inputs :

- a. Detection, intercept, and prioritization state matrices which describe the site's ability to detect and intercept all targets during all time steps.

b, Site File This file includes :

- 1) A time step scheduling matrix ;
- 2) A target prioritization waiting list ;
- 3) The detection, intercept, and prioritization state vectors for the current time step ; and
- 4) Site operational data such as operational status and maximum track capacity.

2. Read State Vectors

Every time step will require the loading of the current detection, intercept, and prioritization state vector into the site file.

3. Search

The value of $d_j(t)$ will be checked to see if the site can detect target j in the current time step.

- a. If $d_i(t) = 0$, no detection will be scheduled and all future scheduling will be cancelled.
- b. If $d_i(t) = 1$, the site will perform scheduled events.

4. Perform Events

If an event is scheduled, the event will generally be performed. If the event calls for the site to fire, the intercept state vector will be checked.

- a. If $I_i(t) = 0$, the target is out of range.
- b. If $I_i(t) = 1$, firing will be performed.

Mode of control, site track capacity, and prioritization can all change the performance sequence.

5. Schedule Future Events

The performance of an event subsequently calls for the scheduling of the next event in the engagement sequence. This scheduling is a function of the time delay distributions. Details concerning the time delays are discussed in Appendix H. The outcome of a previous event of a previous event may also abort future scheduling.

6. Update State Vectors and Site Files

The scheduling of future events requires that the time step scheduling matrix be updated. The outcomes of events must also be reflected in the site files and states vectors. For example, when a target is destroyed, the elements pertaining to the target in the detection matrix will be changed to zero for all future time steps. This will prevent any other site from engaging or continuing to engage the target.

F. COMPUTATIONAL EFFICIENCY

The major steps described in the previous section will be performed for every site and every target during each time step. In most cases, the calculations merely involve determining whether the value of a variable is zero or one. The looping can be performed very quickly and presents no major processing problem. Scheduling events involves changing the value of a cell in a scheduling matrix to some integer value. In general, the bulk of the cumbersome processing, terrain evaluation, radar line-of-sight determination, and intercept calculations have been performed in the pre-processing stage.

G. A DESCRIPTION OF THE MODEL DESIGN

1. Data Bases

The following section describes the description of the data storage formats used in this model.

a. Detection and Intercept Matrices

A detection state matrix is established for each site. The format is follows.

		TARGETS						
		1	2	3	.	.	.	N
K TIME STEPS	1	|	|	|	|	|	|	|
	2	|	|	|	|	|	|	|
	3	| 0 |	| 1 |	| 1 |	|	|	|	| 0 |
	4	|	|	|	|	|	|	|
	.							
	.							
	.							
	.							
	K	|	|	|	|	|	|	|

Figure 5.3 A Detection State Matrix For One Site.

When state vectors are updated for a site during time step three, row three is read into the site file. The site has target two in its detection envelope during time step three. Therefore the entry in element (3,2) of this matrix has a value of one.

The intercept state matrix is formatted in the same manner.

b. Prioritization State Matrix

The prioritization state matrix is established in the following format.

		TARGETS						
		1	2	3	.	.	.	N
K TIME STEPS	1	|	|	|	|			|
	2	| 1	| 1	| 1	|			| 0
	3	|	|	|	|			|
	4	|	|	|	|			|
	.							
	.							
	.	| 0	| 0	| 0	|			|
	.							
K		|	|	|	|			|

Figure 5.4 The Prioritization State Matrix.

When a site has its prioritization vector updated in time step two, row two is read into the site file. In this case, all sites receive the same row. The value of one in element (2,3) of the matrix indicates that target three was attacking the defended area during time step two.

c. Tracking Status Vector

The tracking status vector is a single row matrix which is read into the site file during each time step. Its purpose is to control multiple tracking of targets when the mode of control is centralized. The format of the vector is as follows.

	TARGETS									
	1	2	3	.	.	.	.	.	.	N
TRACKING STATUS	| 0 |	| 1 |	| 1 |	| 0 |	|	|	|	|	|	| 0 |

When the air defense sites are operating under a centralized mode of control, the controller will allow a target to be tracked by only one site. For example, when a site achieves track on target one, the value in element 1 changes from one to zero. If another site attempts to track the same target, the program will check element one. Since the value is zero, no track will be allowed. A value of one in element 3 indicates that no site is tracking target three.

When the mode of control is autonomous, the tracking status vector is ignored.

d. Site File

This file is also in matrix form. It has the following format.

(1) Status - The row labeled status indicates the operational status of the site. A value of one implies that the site is operational. A value of zero indicates that the site cannot perform its mission.

		N TARGETS									
		1	2	3	.	.	.	.	.	.	N
D(3)		0	1	1							
I(3)		0	0	0							
P(3)		1	1	1							0
T		1	1	1							1
STATUS		1									
TRACK CAPACITY		3									
TRACK LOAD		1									
1											
2											
3		1	1	1							0
4											
.											
.											
K											

Figure 5.5 A Site File During Time Step Three.

(2) Track Capacity - This is the maximum number of targets which the site can simultaneously track.

(3) Track Load - This is the number of targets which the site is currently tracking.

2. Performance and Scheduling of Events

The performance and scheduling of events described in Section E is dependent upon several variables. This section will present the factors which must be considered so that the steps of the engagement sequence may be correctly carried out.

a. Detection - A target detection will be scheduled when the value of the appropriate element in the detection state vector is one. If the value changes to zero before the detection can occur, the scheduling will be cancelled. Moreover, this change of value will result in the scheduling cancellation of any other event such as track or fire.

b. IFF - When IFF is performed, a positive response will cause the site to cease acquisition. In this model, a positive IFF response will cancel further scheduling. On the other hand, a negative IFF response will usually cause the program to schedule a track event. There are two exceptions to this sequence:

- 1) In the centralized mode, if the track state vector indicates a value of one, track will not be scheduled. In the case, the target is already being tracked by another site.

- 2) If the site has a track load equal to its track capacity, then a track on the current target will not be allowed.

Even though a track is not scheduled, the target is entered on the site's waiting list for possible future tracking.

c. Track - When track is performed, the site load capacity value is increased by one. Furthermore, in the centralized mode of control, the target's element in the track state vector is changed from one to zero. Fire will be scheduled upon the performance of track.

d. Fire - The fire event will be performed only when the value of the appropriate element in the intercept state vector has a value of one. If the value is zero, the target is considered to have gone out of range. The site will drop

this target from consideration. The site waiting list will be searched to see if there is another target ready to be tracked. The performance of the fire event triggers the scheduling of intercept.

e. Intercept - When intercept is performed, the assessment event is automatically scheduled.

f. Assessment - When assessment is performed, the outcome is based upon the site system probability of kill. If the target is destroyed, several file manipulations occur.

1) The detection state element is changed to zero for all future time steps and for all to engage an aircraft which no longer exists.

2) The site decrements its track load capacity by one.

3) The site searches its waiting list for another target which may have been previously acquired but not tracked.

If the target is not destroyed and the detection state vector still indicates a value of one, the site will re-engage.

In summary, it is possible to design file handling so that accurate simulation of air defense engagements are achieved.

VI. CONCLUSION

This thesis has critiqued the air defense submodels in VECTOR-2 and CORDIVEM and provided a description of a general approach to modeling air defense using an efficient model design.

The critique of current models has emphasized the errors which occur in the prediction of attrition rates when aggregate methods are employed. Furthermore, the omission of terrain, electronic warfare, and command and control factors have been cited as major weaknesses. The proposed design has incorporated higher resolution models of terrain, command and control, target prioritization, and enemy ECM. These models have been added without overburdening the air defense simulation. Maximum use has been made of pre-processing and off-line calculations.

The proposed model design offers a framework for future model building. It emphasizes the structure necessary to create realistic models of the air defense engagement process. As mentioned in previous chapters, the aggregation of many modeling factors is very difficult and can produce misleading conclusions. The general trend has been towards the building of more realistic attrition rate models using efficient high resolution methods. These methods allow the analyst to incorporate the effects of overlapping coverage, multiple kills, and system malfunctions more accurately. Furthermore, this approach gives decision makers a better understanding of the air defense process.

The reader is invited to employ this general design approach as an architecture for model construction. Each model will, of necessity, be modified to suit particular modeling objectives. However, the overall approach will provide a useful point of departure.

APPENDIX A

AIRCRAFT MOVEMENT

The simulation of aircraft movement can be performed in several ways. It is possible to design the simulation so that many of the detailed calculations can be accomplished off-line. Such an approach could improve the resolution of the VECTOR-2 and CORDIVEM air defense models with little additional computational overhead.

Enemy aircraft flights can be planned to take advantage of terrain masking. In Figure A.1, below, a typical flight path is shown.

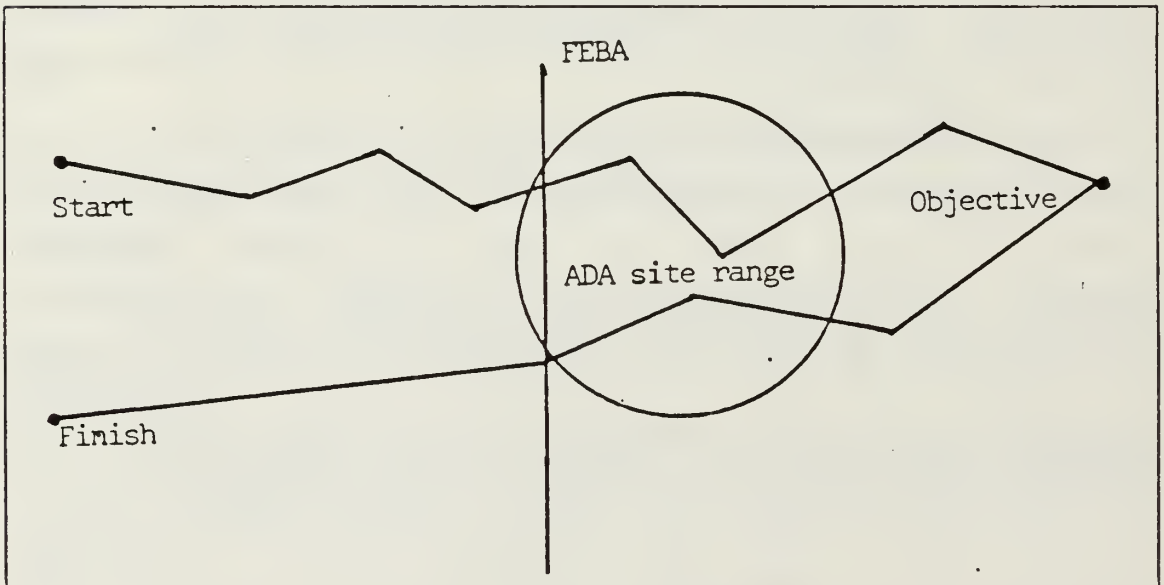


Figure A.1 A Typical Flight Path.

A flight path can be described as fololows:

1. Start time and initial position; and

2. Heading, distance, altitude, and speed for each leg of the flight.

By using a broken segment flight model, enemy flight plans can be prepared in any level of detail desired. These flights will be much more realistic and will reflect the type of tactics commonly employed by the enemy.

The description of the flight path can be transformed to a different format which will facilitate radar line-of-sight calculations. An off-line program can transform the broken line segment format into a grid point and altitude description. For each time step of the simulation, the flight path can be described using:

1. The coordinates $x(t)$ and $y(t)$, from the grid terrain model discussed in Appendix B; and
2. The altitude, $a(t)$.

This transformed description will be used to perform the calculations described in Appendices B through F.

APPENDIX B

A DESCRIPTION OF A GENERAL TERRAIN MODEL

Several large scale combat simulations have employed terrain models to perform mobility and line-of-sight calculations. The following model will be used as a basis for evaluating terrain masking of enemy aircraft.

Assume that the entire battle area is divided into rectangular grid spaces. Each grid space contains a block of uniform height, h , which is the average altitude of all terrain features in the grid square. Figure B.1, below, illustrates a typical grid. The average altitudes are given in feet.

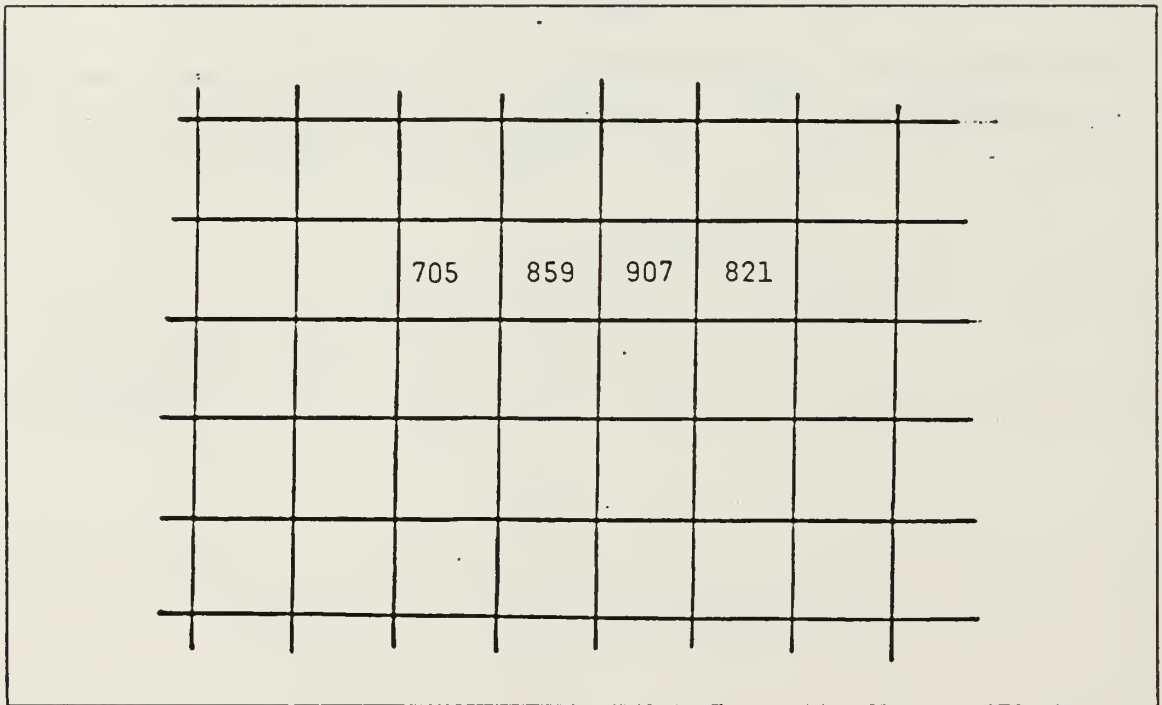


Figure B.1 Average Altitude Grid.

The average altitude can be approximated in several ways. One method is to determine the altitude of each grid square corner and average these four measurements. More sophisticated averaging techniques, such as sampling or numerical integration, could also be employed. In any case, the construction of the average altitude grid can be performed to any desired degree of resolution in an off-line program. Once completed, the grid could serve as a data base for several subprograms in the entire combat simulation. It is also possible that the average altitude data may be one particular parameter in a more detailed terrain model accessed in the simulation.

APPENDIX C
CONSTRUCTION OF A MINIMUM ALTITUDE GRID

This appendix will develop a method for calculating the entries in a minimum altitude grid. This grid will be used in Appendix D to determine radar line-of-sight.

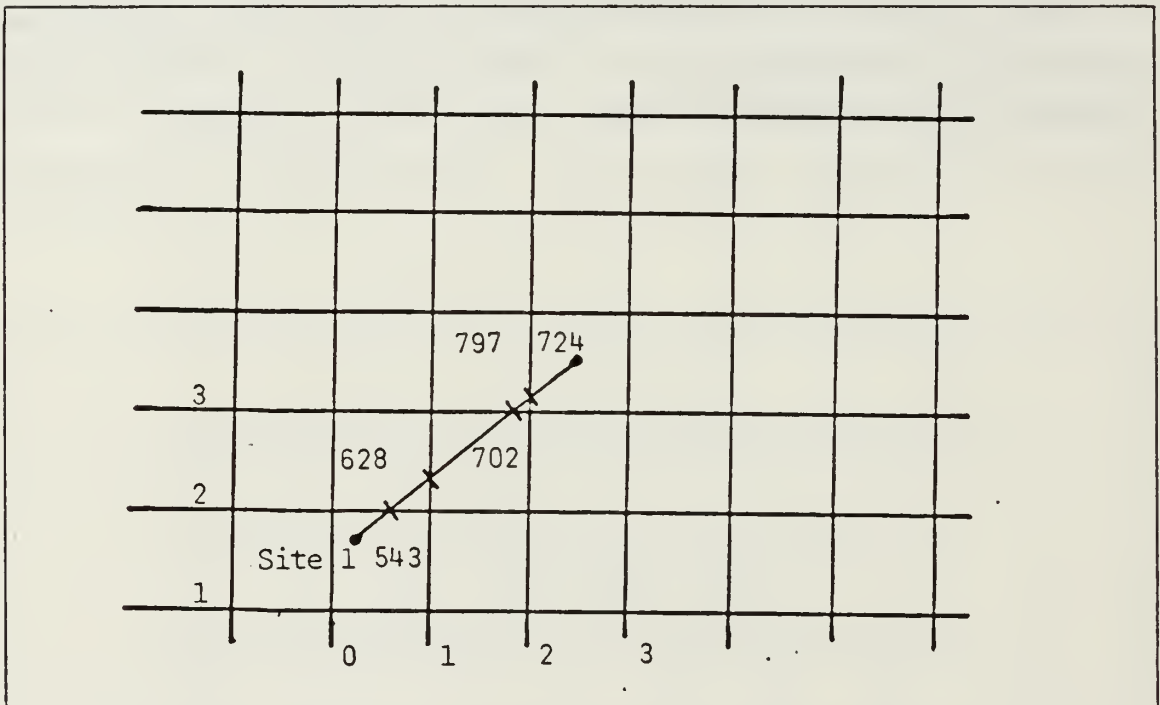


Figure C.1 Average Altitude Grid.

Consider the average altitude grid shown in Figure C.1, above. The line-of-sight from Site 1 to the center of grid square (2,3) will now be analyzed. A profile of this line-of-sight is shown in Figure C.2, below.

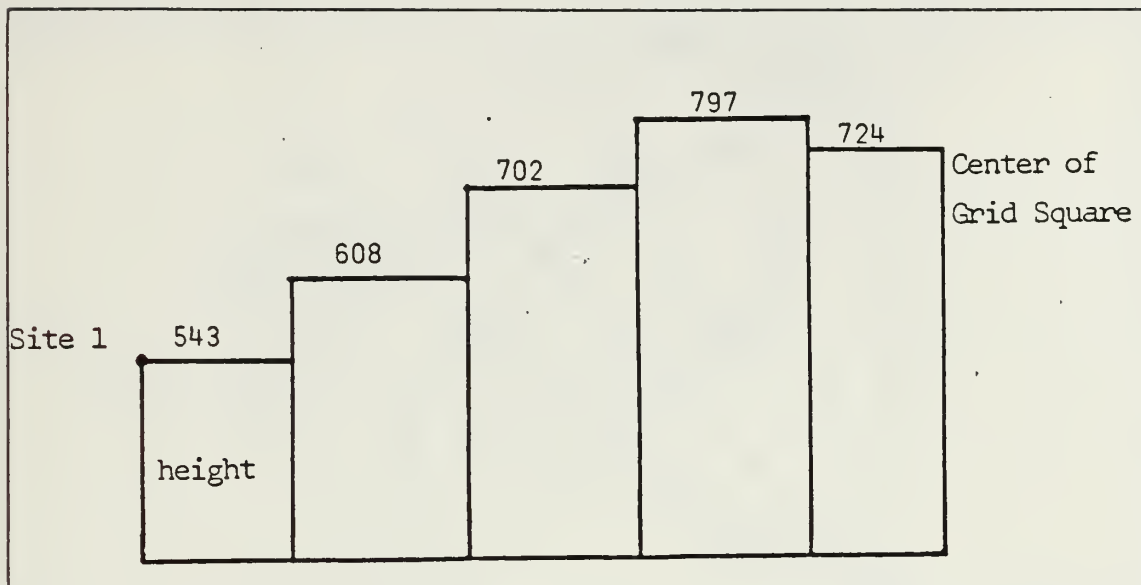


Figure C.2 Profile of Average Altitude.

The profile can be adjusted for earth curvature, as shown in Figure C.3, below.

Drawing a ray, AB, from Site 1 through the edge of the first block illustrates the terrain masking that the first grid square creates. Based on the first grid square masking, the minimum altitude required for radar line-of-sight to a target flying over grid square (2,3) is calculated as follows.

The polar equation of ray (A,C), assuming the origin is at the center of the earth, is:

$$r \sin(\theta) = m r \cos(\theta) + R_e + s \quad (1)$$

where,

m = the cartesian slope of the ray

s = average altitude of the grid square
where the site is located.

R_e = radius of the earth.

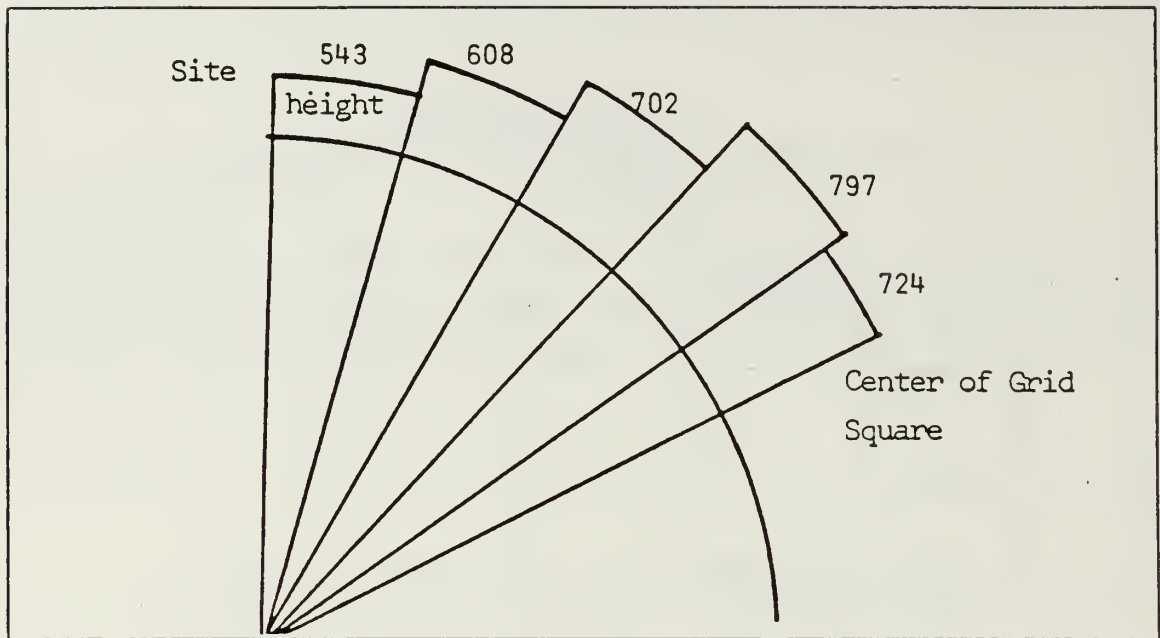


Figure C.3 Profile of Average Altitude
Adjusted For Earth Curvature.

Let l_1 be the lateral range from Site 1 to the edge of the first block (see Figure C.4). Let h_1 be the average altitude of this block. Then the points A and B, expressed in polar coordinates, (r, θ) , are:

$$A = (Re + s, \frac{\pi}{2})$$

$$B = (Re + h, \frac{\pi}{2} - \frac{l_1}{Re})$$

The slope, m , can be expressed in terms of Re , s , h_1 , l_1 as follows. Letting

$$r = Re + h_1 \quad \text{and} \quad \theta = \frac{\pi}{2} - \frac{l_1}{Re}$$

Equation (1) becomes :

$$(Re+h_1) \sin(\frac{\pi}{2} - \frac{l_1}{Re}) = m(Re+h_1) \cos(\frac{\pi}{2} - \frac{l_1}{Re}) + Re + s$$

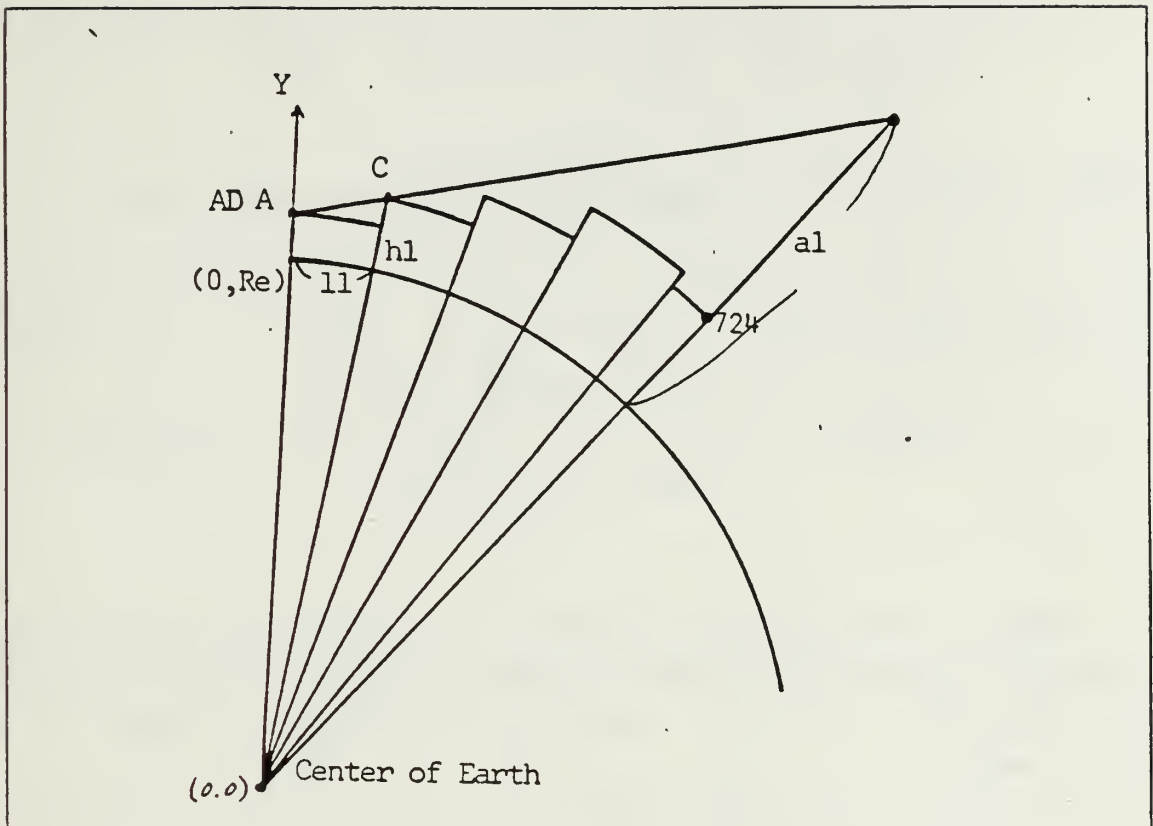


Figure C.4 Calculating Minimum Altitude, Al.

$$\text{and, } m = \frac{(Re+h1) \cos(-\frac{11}{Re}) - Re - s}{(Re+h1) \sin(-\frac{11}{Re})} \quad (2)$$

Letting L = lateral range from Site 1 to the center of grid square (2,3), point C can be expressed in polar coordinates as

$$(Re+al, \frac{\pi}{2} - \frac{L}{Re})$$

Substituting the above point into equation (1), yields the following expression for al, the minimum altitude:

$$a_1 = \frac{Re + s}{\sin\left(\frac{\pi}{2} - \frac{L}{Re}\right) - m \cos\left(\frac{\pi}{2} - \frac{L}{Re}\right)} - Re$$

Using equation (2), a simplified expression for a_1 is,

$$a_1 = \frac{Re + s}{\cos\left(\frac{L}{Re}\right) - \frac{(Re+h_1) \cos\left(\frac{l_1}{Re}\right) - Re - s}{(Re+h_1) \sin\left(\frac{l_1}{Re}\right)}} - Re$$

Thus, given Re, s, h_1, l_1 , and L , the minimum altitude required because of terrain masking by the first block can be calculated. If h_1 is less than s , the slope of ray AC is zero, and

$$a_1 = \frac{Re + s}{\cos\left(\frac{L}{Re}\right)} - Re$$

As one proceeds across along the line-of-sight path in Figure C-1, four grid blocks are encountered. Therefore, minimum altitude calculations would be performed four times. These four altitudes, A_1 through A_4 , are shown in Figure C.5, below

The minimum altitude entry, a_{23} , for grid square (2,3) in relation to Site 1, is:

$$a_{23} = \text{maximum} (a_1, a_2, a_3, a_4)$$

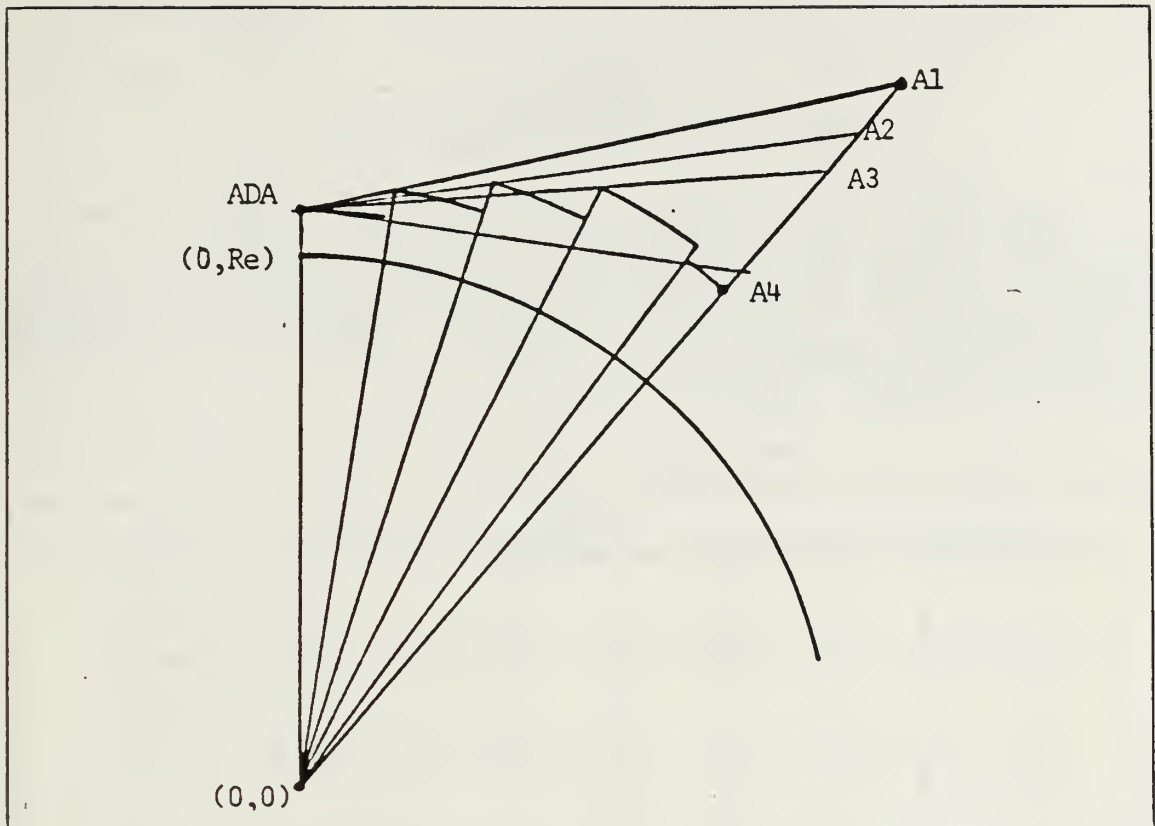


Figure C.5 Minimum Altitudes Along The Line-Of-Sight.

This procedure must be repeated for every grid square located within radar coverage of Site 1. Then, the Site 1 minimum altitude grid would be complete.

APPENDIX D
LINE-OF-SIGHT DETERMINATION

One method of determining approximate radar line-of-sight is to use the minimum altitude look-up table developed in Appendix C. Figure D.1, below, illustrates a minimum altitude grid for Site 1.

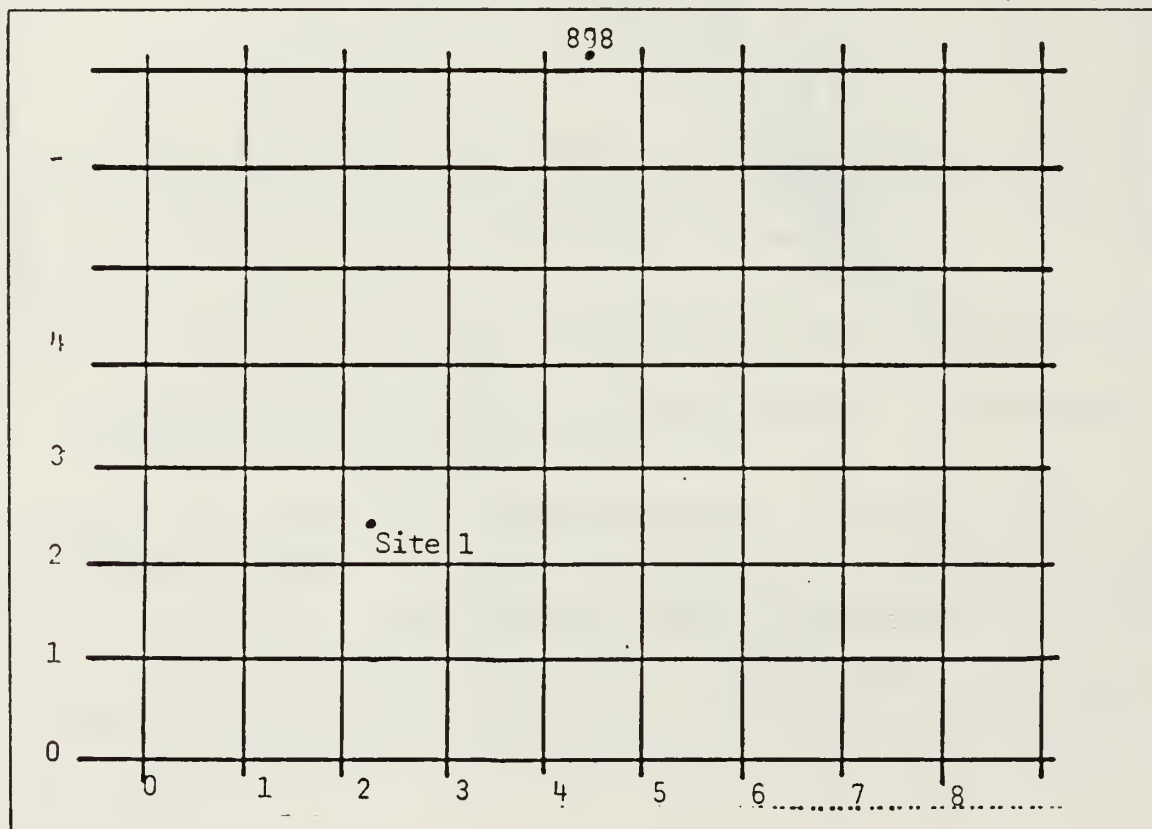


Figure D.1 Minimum Altitude Grid For Site 1.

As an example, assume that an aircraft is flying over grid square (4,7) at an altitude of 700 feet. Site 1 does not have radar line-of-sight with this aircraft because its altitude is less than 897 feet. This line-of-sight check can be expedited by creating a look-up table for each site in the air defense system. The look-up function is not time consuming. Details of calculating the minimum altitude entries for the table are discussed in Appendix C. These calculations can be done off-line and input into the simulation data base. The accuracy of the minimum altitudes can be improved by refining the grid. Again, this additional resolution does not greatly affect the main model calculations.

APPENDIX E
DETERMINING THE POSSIBILITY OF DETECTION

The procedure for deciding if a site can detect a given target involves the following steps.

1. Using a minimum altitude look-up table, determine if there is radar line-of-sight to the target. If line-of-sight does not exist, no detection will occur.
2. If radar line-of-sight exists, calculate the slant range, X , from the site to the target. If the slant range is more than the maximum acquisition range, R , of the radar, no detection will occur. If slant range is less than or equal to the maximum acquisition range, a detection is possible.

The calculation of the slant range can be performed as follows.

Consider a target at time, t , with the following parameters:

1. $(X_1(t), Y_1(t))$ is the target grid coordinate.
2. $a(t)$ is the target altitude.

The lateral range, L_1 , of the target from the site at time t is:

$$L_1(t) = \sqrt{(X_1(t) - X_0(t))^2 + (Y_1(t) - Y_0(t))^2}$$

where, (X_0, Y_0) are the grid coordinates of the site.

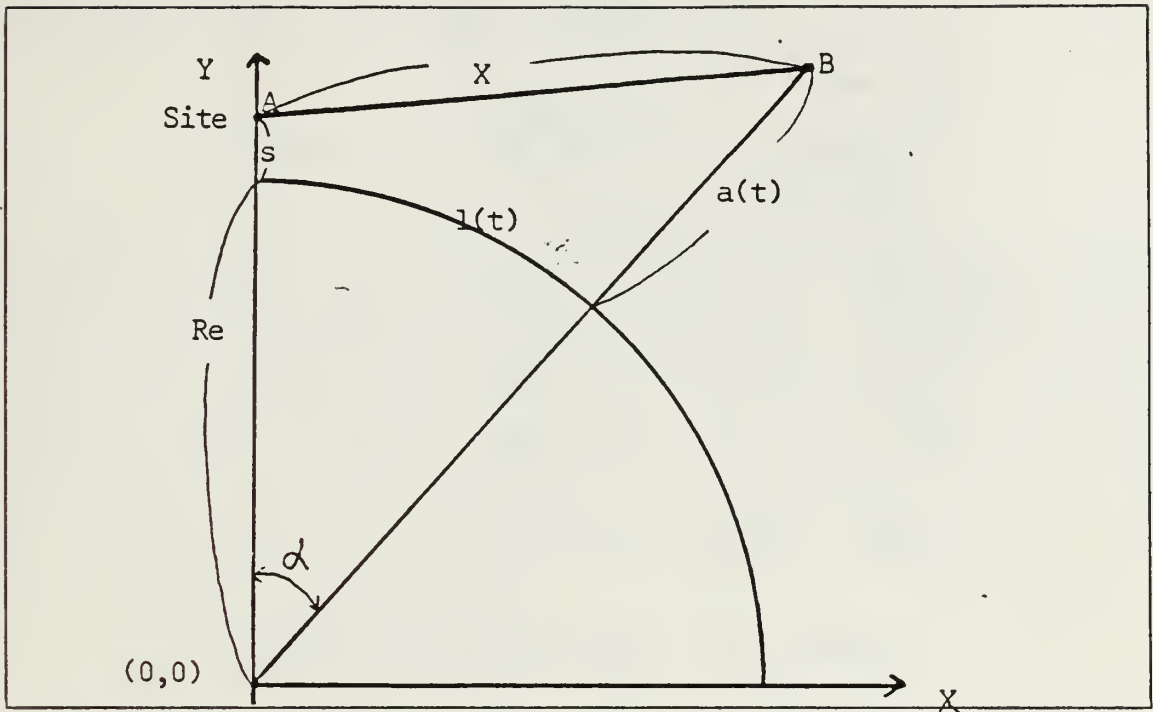


Figure E.1 The Calculation of The Slant Range.

The angle, (α) , between rays OA and OB is $Ll(t)/Re$, measured in radians (see Figure E.2) below.

The slant range, X , can be calculated from the Law of Cosines:

$$X^2 = (Re+s)^2 + (Re+a(t))^2 - 2(Re+s)(Re+a(t)) \cos\left(-\frac{Ll(t)}{Re}\right)$$

where, s = the altitude of the site.

If $X^2 > R^2$, no detection occurs.

If $X^2 \leq R^2$, a detection is possible.

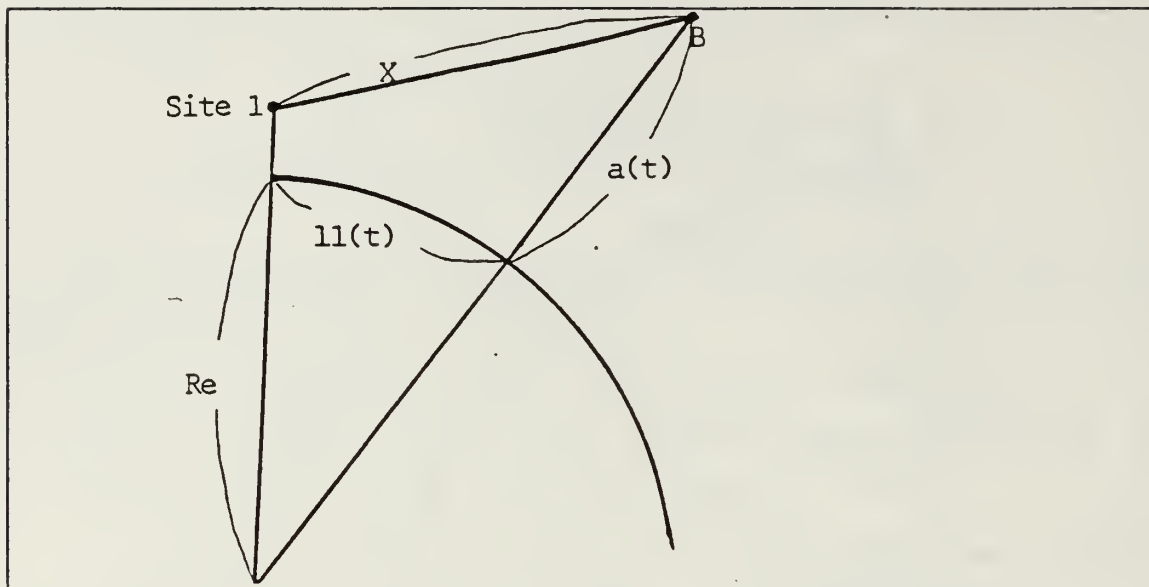


Figure E.2 Computation of Angle.

APPENDIX F
CALCULATING THE SITE DETECTION STATE VECTOR

The purpose of this appendix is to develop an accurate detection state vector using the models and methodology contained in appendices A through E. This detection model will be developed using off-line computations and will be an input to the air defense overflight model. The level of accuracy of the detection model can be determined by the user. It is a function of the accuracies achieved in the :

1. Average altitude model ;
2. Minimum altitude model ; and
3. Aircraft movement model.

The detection state vector is defined as follows. For each time step, t ,

$$D(t) = (d_1(t), d_2(t), d_3(t), \dots, d_N(t))$$

where, N = number of targets generated in the entire simulation.

$$d_i(t) = 0, \text{ when the site cannot detect target } i$$

$$d_i(t) = 1, \text{ when the site can detect target } i$$

The possibility of detection is determined by using the calculations developed in Appendix E. As previously stated, this detection is only a function of detection geometry.

During each time step, the site checks the state of each element of its detection vector. All targets having a value of one can be considered for the engagement sequence. If the

site has been engaging a target during previous time steps, a change of detection state from one to zero will cause a reaction. One approach is to instruct the site to drop the target from consideration. A more realistic decision algorithm could have the site drop a target after two or three successive time steps have indicated a detection state of zero. In many case, the detection vector can accurately simulate a target entering or leaving the radar detection envelope.

In summary, each flight can be flown over its course in an off-line processor. The detection state vector can be calculated for each site and input to the simulation data base. During the simulation, possible detection is determined by examining the elements of the state vector for the time step in question.

APPENDIX G

CALCULATING THE SITE INTERCEPT STATE VECTOR.

Using off-line processing described in Appendix F, a site intercept state vector can be developed. The intercept state vector is defined as follows. For a given site and for each time step, t ,

$$I(t) = (i_1(t), i_2(t), i_3(t), \dots, i_N(t))$$

where

N = number of targets generated in the entire simulation.

$i_j(t) = 0$, implies that a missile fired at target j during this time step will have a predicted intercept point beyond the range capability of the missile system.

$i_j(t) = 1$, implies that a missile fired at target j during this time step will have a predicted intercept point within the range capability of the missile system.

Given an intercept state vector for each site, it is possible to simulate a missile firing range check at the time step in which firing has been scheduled. This range check is nothing more than a zero or one value check during the simulation.

The detailed calculations have been performed off line. The accuracy of the predicted intercept point can be improved subject to desires of the model builder. There are several high resolution missile flight models which could be used without overburdening the air defense simulation.

APPENDIX H

ACCOUNTING FOR SYSTEM/OPERATOR PERFORMANCE TIME DELAYS

The dependence of the time delays on the four major factors, discussed in Chapter 5, can be depicted as follows:

TABLE III
TIME DELAY AND MAJOR FACTOR DEPENDENCE

Time Delay	Factors	Normal Variability	Weather	Enemy ECM	Mode of Control
Td		Yes	Yes	Yes	No
Tt		Yes	Yes	Yes	No
Tf		Yes	No	Yes	Yes
Ti		Yes	No	No	No
Ta		Yes	No	No	No

A. DESCRIPTION OF FACTORS

1. Normal Variability

System and operator performance are not constants. First, acquisition and tracking radars will not always detect and track targets at maximum range. Radar components may not be peaked. Furthermore, radar performance can be a function of operator experience and skill. As a result, the time between each step in the engagement sequence greatly varies.

Missile flight characteristics also vary from target to target. The time between fire and predicted intercept can be modeled as a random variable. Deterministic flight models can also be used. However, their results may have far more accuracy than required.

2. Weather

Heavy precipitation will degrade the performance of most radars. One approach to accounting for the weather factor is to have the user input a desired weather condition:

- a. $W = 0$ implies that weather is not a factor.
- b. $W = 1$ implies that weather degrades radar performance. As a result, time delays will be increased when T_d and T_t are calculated.

3. ECM

If the user desires to consider ECM capabilities, the following inputs may be chosen:

- a. $ECM = 0$ implies no ECM.
- b. $ECM = 1$ implies the enemy is using ECM and the effect is noticeable but does not highly degrade radar performance.
- c. $ECM = 2$ implies the radar performance is significantly degraded.

These ECM conditions are those used in current air defense doctrine. If $ECM = 1$ or $ECM = 2$, the values of T_d , T_t , and T_f will increase.

4. Mode of Control

If the user inputs $M = 0$, this implies that the mode of control is autonomous and there will be no expected increase in T_f . When $M = 1$, the sites are operating under centralized control and T_f will increase (see Appendix E).

The remainder of this appendix will describe an approach to modeling the variability in these time delays. A great deal of research and experimentation will be needed to arrive at more precise distributions for these variables. However, the model design will introduce a framework which can be modified as the model builder desires. For demonstration purposes, the time delays will be modeled as uniform distributions.

B. DESCRIPTION OF TIME DELAY VARIABLES

1. Time Between Maximum Detection and Detection (T_d)

Let T_d be a uniform random variable defined over the interval $(0, b)$. The parameter, b , is a function of factors which are inputs to the overall simulation. Consider the following situation :

- a. Normal detection delays vary from zero to five seconds.
- b. Inclement weather causes delays from zero to seven seconds.
- c. ECM condition 1 generally accounts for delays from zero to five seconds.

In this situation, the detection time delay could be modeled as a uniform random variable on the interval $(0, 17)$. If the user decided to disregard the effects of inclement weather and ECM, the distribution could be defined over the interval $(0, 5)$.

2. Time Between Actual Detection and Tracking (Tt)

Current air defense systems experience several delays during this portion of the engagement sequence. In many cases, a target will return a pulse which can be detected. However, the target returns may not be steady or strong enough for a tracking radar to obtain range gate lock. The delays caused by variable system/operator performance, weather, ECM are similar to those involving the detection process. However, the time delays are often greater in mean and variance.

A uniform distribution could be used to simulate the value of T_t . The interval of definition would generally be defined as (a, b) . There is some lower bound for T_t . Under best conditions, a can be no less than two seconds for systems such as NIKE-HAWK.

3. Time Between Tracking and Firing (Tf)

If the sites are operating under centralized control ($M=1$), the expected value of T_f will increase (see Appendix E). Even when the autonomous mode is in effect, time delays may be encountered because the target is out of missile intercept range. It is possible to track a target and delay firing until the target flies closer to the site. This delay can best be evaluated on a case-by-case basis.

Under some weapons control conditions, the target must be challenged using a Interrogation Friend or Foe (IFF) system. The IFF check usually requires a fixed amount of time. IFF considerations are addressed in Appendix H.

If the user plans to include IFF checks and operate the air defense in a centralized mode, consideration must be given to increasing the expected value of T_f . If a uniform distribution is used, the interval of definition should again be (a, b) , where a is greater than zero.

4. Time Between Firing and Predicted Missile Intercept (Ti)

As mentioned earlier, missile flight models can be used to calculate deterministic time delays. T_i can also be modeled as a uniform random variable on the interval (a, b) where a is the minimum flight time and b is the maximum flight time. These parameters can be calculated using a missile flight model. Missile flight times derive there greatest variability based on the heading and speed of the target. If the missile must intercept a high speed, outbound target, the expected flight time will increase considerably.

5. Time Between Intercept and Completion of Damage Assessment (Ta)

There is a time delay experienced when an intercept is believed to have occurred. The operator must determine if the target has been destroyed or if the missile has malfunctioned. Operators rely on multiple indicators to confirm a kill. T_a is usually the smallest of the time delays but should be considered. If the target continues to fly, the site must decide whether to refire or switch to another target of higher priority (see Appendix G).

APPENDIX I

COMMAND AND CONTROL

The air defense against overflights can be managed using two different modes:

Centralized Control:

Each air defense site is controlled by a higher headquarters. The site may acquire and track targets as it deems appropriate. However, the decision to fire is maintained at headquarters. Typically, this headquarters is the Battalion Operations Central(BOC). The BOC usually controls four firing sites.

Autonomous:

The sites act independently and fire at targets based on hostile criteria.

Centralized control allows for efficient fire distribution. However, it may not be responsive in high density attacks. The autonomous mode allows for quick reaction, but often results in overkill and improper fire distribution.

Air defense simulations can model a choice of mode of control. One approach makes use of the files maintaining status on each site and each target. These files were introduced in Chapter 5.

Consider the situation where the model user selects the centralized mode of control. In each time step, the detection algorithm is performed by each site for each target in the system. When a site detects a target it checks the value of the track state vector. Two situations can occur:

1. If $T = 1$, T is changed to 0, and the site schedules a track event at a later time step. It is the only site allowed to engage the target.

2. If $T = 0$, the site disregards the acquisition and searches for another target.

If the site cannot engage the target successfully, it changes the value of T back to one, so that other sites may attempt to engage. This procedure allows for fire distribution which is realistic.

An additional factor to consider is the additional time delay which may occur between tracking and firing on the target. In the centralized mode, a firing unit must ask for permission to fire after track has been achieved. This additional delay can be built into the time delay distributions described in Appendix G.

In the case where the model user selects the autonomous mode of control, multiple engagements are allowed. The value of T will remain at one. This will allow multiple tracking and firing against one target. Such actions are usual in this mode and occur when sites have overlapping coverage.

In both modes, the site and target status files must be updated to reflect a target kill. This will cause all units to drop the target from their files and avoid multiple kills on the same target. As a result, the attrition rate will not be overestimated.

APPENDIX J

. INTERROGATION FRIEND OR FOE (IFF)

The air defense overflight attrition models in VECTOR-2 and CORDIVEM totally ignored IFF. The IFF process is important for two reasons:

1. The IFF procedure requires some time to execute and may delay firing.
2. The IFF check may be the only means by which the site decides whether the target is friend or foe.

The IFF check may improperly classify a target. The check can be modeled as a Bernoulli trial with conditional probabilities defined as follows.

1. Let P_1 = probability that a friendly target is classified as friendly.
2. Let P_2 = probability that an enemy target is classified as foe.

The user could input the IFF condition as follows:

1. Let $IFF = 0$ if IFF is not in effect.
2. Let $IFF = 1$ if IFF is to be used.

Second, IFF is modeled, the conduct of the simulation will reveal two significant results. First, the sites will devote considerable time to acquiring and tracking friendly aircraft. A positive IFF response will cause the site to disregard the friendly target and search for new target. This loss of time should markedly decrease attrition rate predictions. Second, fratricide may still occur because of

improper IFF responses. If IFF is not modeled the sites will destroy friendly aircraft in greater numbers. Now fratricide will be a significant factor.

APPENDIX K
TARGET PRIORITIZATION AND SELECTION

In the air defense models used in VECTOR-2 and CORDIVEM, target prioritization and selection algorithms were not employed. One technique which can be implemented to simulate a selection process is to tag each target as either attacking or returning to its own territory.

One method of tagging involves the development of a prioritization state vector. This vector is defined as follows. For a given site and time step, t ,

$$P(t) = (p_1(t), p_2(t), p_3(t), \dots, p_N(t))$$

where

N = number of targets in the entire simulation.

$p_i(t) = 1$, when the target i is flying the attack portion of its flight path.

$p_i(t) = 0$, when the target i is flying the return portion of its flight path.

The prioritization state vector will be used to order targets which are on the site waiting list (see Chapter V).

As discussed in appendices F and G, the priority values can be determined in an off-line calculation. During the actual air defense simulation, prioritization is merely a zero or one value check.

As targets are acquired and tracked, the site files are updated. When a site is tracking or attempting to track its maximum number of targets, all other acquisitions can be entered on a site waiting list. When the site drops one of its primary targets, it can search the waiting list and

consider the "attack" or "return" status of the target as a criterion for selection.

Other prioritization rules can be developed. However the tagging, described above, agrees with air defense doctrine. It appears that this form of prioritization can be implemented with minor computational overhead.

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